Final Report *April 1987*

MILITARY SPACE ROBOTICS

By: DAVID R. BROWN WILLIAM T. PARK

Prepared for:

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
INFORMATION SCIENCE AND TECHNOLOGY OFFICE
1400 WILSON BOULEVARD
ARLINGTON, VIRGINIA 22209

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Autonomous systems based on robotics will be essential for future U.S. military programs in space, and new emphasis and priorities for research and development of robotics technology should be adopted now to meet the needs of these programs. A plan of research and development of robotics for military space programs, prepared by SRI International, emphasizes the early use of industrial robotics as a first step in the development of autonomous robots in space. A broad plan is proposed for intelligent robotics: in servicing spacecraft and their payloads, construction in space, ground manufacturing and assembly, and mining of extraterrestrial materials. The plan was presented at a workshop in July 1986, at which military, academic, and industrial experts in space and robotics technology noted shortcomings of the plan and offered suggestions for improving it. The need for a comprehensive, integrated plan was

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19. ABSTRACT (Continued)

generally acknowledged. Major advances in both hardware and software are required, including sensors, effectors, and artificial intelligence for planning and control in a dynamic and changing environment.

SUMMARY

Autonomous robots will be needed in space for future military systems such as the Strategic Defense Initiative. Space systems will have to be designed for servicing by robots, and the manufacture of both space vehicles and their payloads will be made more economical by the use of robotics in factories and launch facilities. Advances in robotics, including artificial intelligence (AI), will change the present economic balances throughout the whole cycle of design, production, checkout, launch, operation, and main-tenance of space systems. Consequently, a plan for military robotics in space must be broad, encompassing all aspects of space systems.

A plan that looks far into the future, as this one does, will be inaccurate, but it does define R&D vectors that apply to near-term decisions about R&D, and it enables setting R&D priorities in relation to both short-term and long-term goals. A strawman plan was developed by SRI International and was presented at a one-day workshop attended by well over 100 persons. The work-shop also included presentations by Col. James L. Graham, SDIO, and Dr. Melvin D. Montemerlo, NASA Headquarters. The plan, introduced by Dr. Rodger A. Cliff, DARPA, and presented by Mr. David R. Brown and Dr. William T. Park, SRI International, looks into the 21st century, to about year 2010. It includes research and development of autonomous robots for servicing spacecraft and for construction in space, automation of the manufacture and assembly of spacecraft and their payloads, and mining of extraterrestrial materials. The R&D plans require multiple, simutaneous efforts to obtain the advanced sen-sors and effectors that will be needed, and the software to go with them. Advances in AI will be needed for geometric representation, coordination of multiple, autonomous systems, planning in a dynamic environment, and for other tasks.

After the presentation of the plan, five working groups were formed, one for each of the major components of the plan, as follows:

- Inspection, servicing, maintenance, and repair, chaired by Dr. James S. Albus, NBS.

- Construction in space, chaired by Dr. Kelli Willshire, NASA Langley Research Center.

- Manufacturing, chaired by Mr. James E. Hollopeter, General Dynamics

- Extraterrestrial harvesting, chaired by Prof. Theodore J. Williams, Purdue University.

- Research and development, chaired by Prof. Robert Cannon. Stanford University.

The findings of the working groups were presented and discussed with all of the workshop participants. In general, the working groups agreed on the need for a plan and the importance of robotics in space. The working groups noted some omissions, disagreed with some of the plans, and expressed doubts about some objectives. The major omission was estimated cost, important because cost is a driving force for automation. The strawman plan advocates early use of industrial robotics in space to demonstrate the feasibility of space robotics, but the working group that reviewed that part of the strawman plan recommended against flying industrial robots. Instead, it recommended more intensive testing on the ground of robots specially designed for space. The participants in the workshop agreed that the technology for extraterrestrial harvesting (mining) was attainable, but expresses doubts about the require-ment for doing it.

The strawman plan, with the comments of the working groups, consti-tutes a valuable foundation for a broad plan of action. More work is needed to define requirements, examine costs, and add missing pieces of the plan, but it represents a comprehensive approach to development of military space robot-ics. It can help to establish priorities for research and development and lead to an earlier realization of important national-security objectives. The work-shop did increase the awareness of the military space community of the poten-tial of robotics technology, some of it already available. It also emphasized the importance of a broad, comprehensive, and far-reaching plan, encompassing design, manufacture, launch, and maintenance. The beginnings of the needed plan, established here, should be used as the foundation for a continuous plan-ning effort that includes all of the interdependent elements of military space robotics.

CONTENTS

LIST OF ILLUSTRATIONS

1 INTRODUCTION

The work reported here was undertaken for DARPA and is based on these two theses: autonomous systems based on robotics will be essential for future U.S. military programs in space, and new emphasis and priorities for research and development of robotics technology should be adopted now to meet the needs of these programs.

These theses arose from consideration of future space programs, including programs that extend well into the 21st century, and what will be possible when the technology is available. With such a vision of the future, a different emphasis on technology for space robotics emerges. These future needs for space will influence the development of the technology; this work is aimed at defining the influencing vectors for current R&D plans.

Earth-orbiting satellites for military communications and surveillance provide some motivation, but the projected needs of the Strategic Defense Initiative (SDI) provide even stronger impetus. Consideration of the needs of the SDI adds to the significance and validity of the approach advocated.

To enlist the support of the groups that can effect the needed research and development (R&D), the Defense Advanced Research Projects Agency (DARPA) conducted a workshop with participants from the R&D, industrial, and military communities. The workshop, held in July 1986, was well attended by eminent members of all three communities, who are listed in the Appendix. During the day-long workshop, these representatives contributed their views of what was needed in response to a strawman R&D plan that was proposed at the start of the day by SRI International.

In outline, this report consists of:

- Background on the needs and the technology base.
- The strawman plan presented by SRI.
- Comments and counterproposals by the participants at the workshop.
- Conclusions and recommendations.

2 BACKGROUND

The workshop was held on 28 July 1986, at a BDM Corporation building in McLean, Virginia. Background for the scope of the workshop was provided by Dr. Rodger A. Cliff, DARPA, for the SDI by Col. James L. Graham, SDIO, and for NASA's automation and robotics program, by Dr. Melvin D. Montemerlo, NASA Headquarters.

2.1 Future Military Needs in Space

Fabrication, transport, assembly, and maintenance of structures in earth orbit will be needed for future military systems. Practical and economic means will be required to put into orbit large numbers of similar objects, including very large objects and very large masses. Large structures will require the means for construction and assembly in space. Supply, maintenance, and repair will require additional deliveries into orbit and intelligent control. These supporting operations will be required beyond low-earth orbit, where no presently planned systems can provide support. Objects in space will need to be designed for service by autonomous robots. Objects in space will have to be hardened for protection against directed-energy weapons, kinetic-energy weapons, and natural radiation. Extraterrestrial materials (ETM) will be preferable as a lower-cost alternative to earth-launched materials when large total mass is required for hardening, or when very large objects or large numbers of objects must be constructed.

Present-day launch and in-orbit operations are too costly and unreliable to support space-defense activities on the scale that will be required. Cost to orbit is high because building and launching conventional spacecraft (whether expendable or reusable) are extremely labor intensive. In-orbit labor costs are high because of (1) high labor overhead for routine monitoring and operation of spacecraft and (2) the high weight penalty for life support equipment.

Col. Graham presented "An SDI Perspective on Military Space Robotics" in which he emphasized the importance of influencing the design of the future SDI system as early in the R&D process as possible. He stated that potential applications of robotics for the SDI include

- Production of spacecraft, payloads, and ground systems.

- Spacecraft maintenance and servicing, including assembly of large space structures, hazardous operations, inspection via telepresence, removal/replacement of exchangeable items, replenishment of consumable items, cleanup/debris removal.

- Ground processing of launch systems, including payload inspection, test, and checkout, ground maintenance systems, and handling of materiel.

- Test, checkout, and maintenance of ground-based weapon systems.

Col. Graham also expressed concern about the present lack of definition of SDI requirements, the need for analyses of cost and operational benefits, the difficulties in integrating multiple efforts, the establishment of realistic priorities, and the need for an integrated research approach for SDI and other applications.

2.2 Robotics Technology Base

Progress in intelligent automation and robotics has implications for operations in space in the 1990-to-2010 period. Research in robotics and artificial intelligence (AI) provides a base for software for intelligent perception, problem solving, and control. In addition, appropriate mechanisms proven in industry can be adapted for space. Many R&D programs, such as DARPA's autonomous land vehicle (ALV) program, will yield developments that can be incorporated in future space robots, including expert systems, planning systems, vision systems, natural language interfaces, and hardware and software for parallel processing. Advanced industrial robotics technology that can be adapted for use in space includes sensors, vision software, manipulators (hands, wrists, and arms), control algorithms, and programming languages.

Intelligent automation and robotics will influence the whole spectrum of space operations, including

- Automated terrestrial manufacture of launch vehicles, spacecraft buses, spacecraft payloads, space-based weapons, and robots.

- Intelligent automation of launch and ground operations.

- Erection, assembly, and construction of large objects in space.

- Inspection, servicing, maintenance, and repair of space systems, including the robots themselves.

- Manufacturing in space.

- Mining of extraterrestrial materials (ETM).

In his description of the NASA program for space automation and robotics, Dr. Montemerlo stressed an approach based upon initial use of teleoperators with later, step-by-step introduction of autonomy. The NASA program is currently focused on telerobotics technology for multimanipulator control. A two-armed teleoperated manipulator will be demonstrated in FY

1987. The demonstration task is to perform functions like those involved in servicing a satellite, for example, replacing a module. Successive demonstrations at approximately three-year intervals will incorporate increasing levels of autonomy, the human operator eventually assuming a supervisory role. A telerobotic servicer based on the FY 1987 and subsequent demonstrations is planned for use in assembly and servicing of the space station. The demonstrators are being developed at Jet Propulsion Laboratory (JPL), with several other NASA centers involved in other aspects of the program to achieve systems suitable for space flight.

3 SRI'S STRAWMAN

The SRI strawman plan was presented by Dr. William T. Park, beginning with an overview of the proposed plan in which he described the supporting relationships between the elements of the plan (Figure 1). The major elements of the plan are

- Orbital servicing
- Construction in orbit
- Ground manufacturing
- Extraterrestrial harvesting
- R&D program in robotics.

These elements are described in more detail later. The last element, an R&D program in robotics, supports all of the other elements, but other supporting relationships are also important, for example, between orbital servicing and ground manufacturing. Design of spacecraft or payloads to be manufactured by means of robots, in the ground manufacturing part of the plan, must produce objects that can readily be serviced in orbit, by autonomous robots.

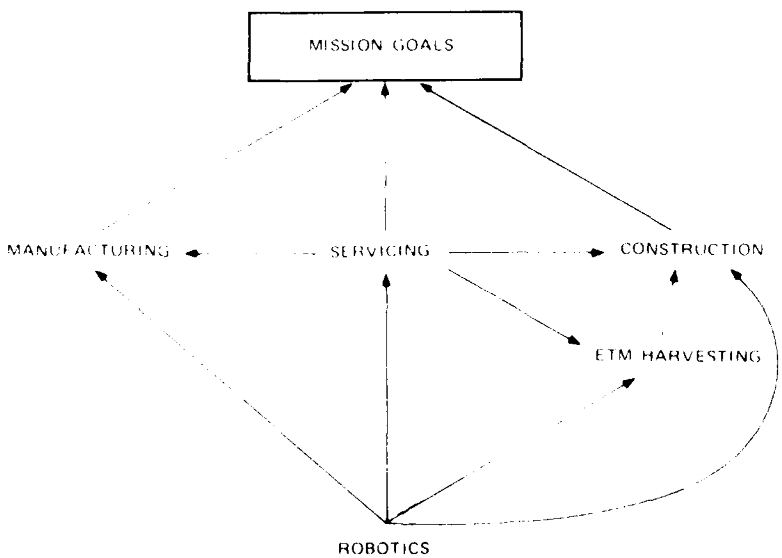


Figure 1 Supporting Relationships Among Programs

A rough development schedule is indicated in Figure 2; it shows the earliest dates when some significant and useful capability might be possible for each of the first four elements of the plan. A more detailed development schedule for each of these elements is presented later.

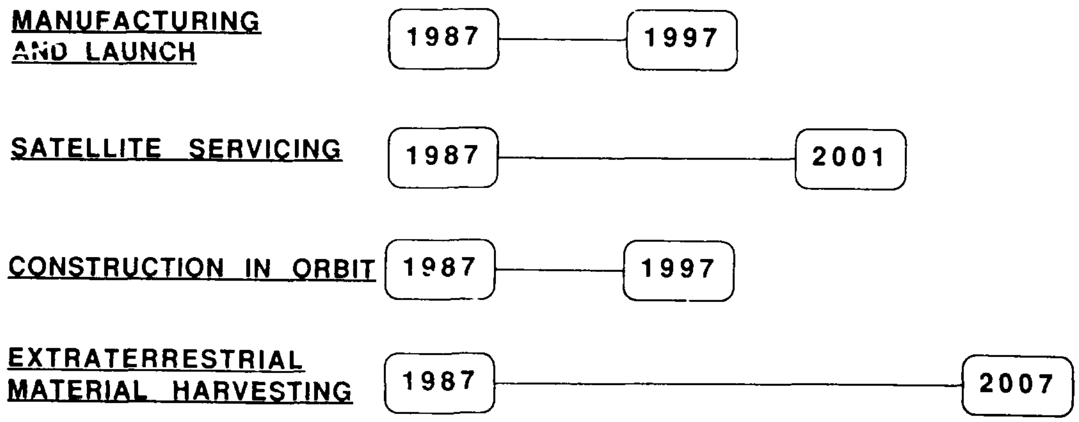


Figure 2 Development Schedule

3.1 Orbital Servicing and Construction

Orbital servicing and construction, the first two elements of the plan, have much in common and so are discussed together. An example of a need for construction in space is illustrated in Figure 3, taken from an advertisement by McDonnell Douglas.

3.1.1 Critical Issues

A number of critical issues have been identified for orbital servicing and construction by autonomous robots. The desired technical objectives for autonomous robots for servicing and construction are to

- Design satellites and space vehicles for compatibility with automatic servicing methods.
- Design the servicing robots so that they can service and repair each other and other robots.
- Achieve a high level of dexterity in robot manipulation.
- Provide free-flight capability.
- Provide on-board automatic piloting capability.
- Automate proximity operations such as rendezvous, docking, capture, rigidization, and stabilization.

Figure 3 Assembly of a Large Structure in Space [Source: *Aviation Week and Space Technology*, Vol. 123, No. 9, outside back cover (2 September 1985).]

- Design construction robots so that

  -They can be serviced and repaired by the servicing robots.
  -They have a long reach.
  -They can safely handle an object with a large mass or moment of inertia.
  -They can travel over large structures without consuming reaction mass.

- Design orbiting structures for compatibility with automatic construction methods.

- Develop control methods that enable multiple construction robots to work as a team, without interference and with co-operation.

3.1.2 Servicing R&D Plan

A series of demonstrations of robotics technology for servicing in space is shown in Figure 4. The proposed demonstrations span a period of at least two decades. Intermediate supporting demonstrations, some in earth-based laboratories and some in space, will have to be planned and carried out. Useful technology for servicing objects in space would, of course, become available before the end of the entire series of demonstrations indicated in the figure. The demonstrations are designed to verify increasing robot capabilities and focus research on future needs.

An important feature of the plan in Figure 4 is the early demonstration of industrial robotics in space. The first five demonstrations use industrial robots, such as a Puma. They would start with a Puma in a zero-gravity aircraft and end with such an industrial robot on the orbiter or other platform, such as the Eureca. This approach is advocated in order to learn from experience the problems that will be encountered in space. Whatever industrial robot is used, it would be evaluated for the specific demonstration and modified as necessary to prevent any predictable malfunction. The first robots specifically designed for space would be used in the sixth demonstration, when the usefulness of robot servicing would be realized.

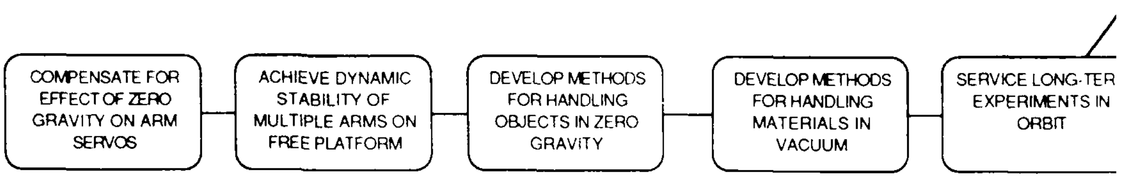
3.1.3 Off-the-shelf Industrial Robotics

Initial demonstrations of robotics technology in space can use the best available, off-the-shelf, industrial robotics. Off-the-shelf capabilities that can be exploited include

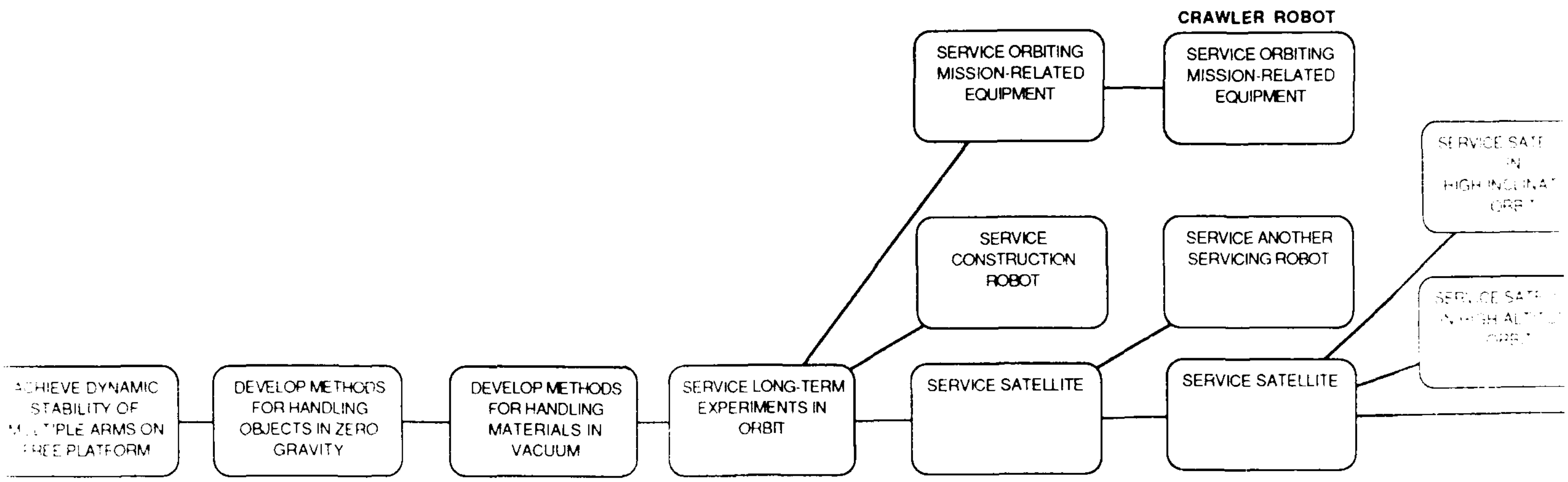
- Machine sensing to compensate for indeterminacies in the position or shape of objects.

- Robot-control software for inspection, servicing, and maintenance.

- Use of latest technology from research laboratories.



LAUNCH VEHICLE	ZERO-GRAVITY AIRCRAFT	ZERO-GRAVITY AIRCRAFT	AIRIES SOUNDING ROCKET	AIRIES SOUNDING ROCKET	ORBITER, EURECA PLATF
ROBOTIC TECHNOLOGY	1 INDUSTRIAL MANIPULATOR	2 INDUSTRIAL MANIPULATORS	2 INDUSTRIAL MANIPULATORS IN SPACE SUITS	2 INDUSTRIAL MANIPULATORS IN SPACE SUITS	2 INDUSTRIAL MANIPULATORS IN SPACE SUITS
ENVIRONMENT	ATMOSPHERE	ATMOSPHERE	PRESSURIZED MODULE	UNPRESSURIZED MODULE	SPACE



ZERO-GRAVITY AIRCRAFT	AIRIES SOUNDING ROCKET	AIRIES SOUNDING ROCKET	ORBITER, EURECA PLATFORM	ORBITER, RMS	ORBITER, OMV	OTV
2 INDUSTRIAL MANIPULATORS	2 INDUSTRIAL MANIPULATORS IN SPACE SUITS	2 INDUSTRIAL MANIPULATORS IN SPACE SUITS	2 INDUSTRIAL MANIPULATORS IN SPACE SUITS	2 SPACE-QUALIFIED MANIPULATORS	2 SPACE-QUALIFIED MANIPULATORS	3 SPACE-QUAL MANIPULATORS
ATMOSPHERE	PRESSURIZED MODULE	UNPRESSURIZED MODULE	SPACE	SPACE	SPACE	SPACE

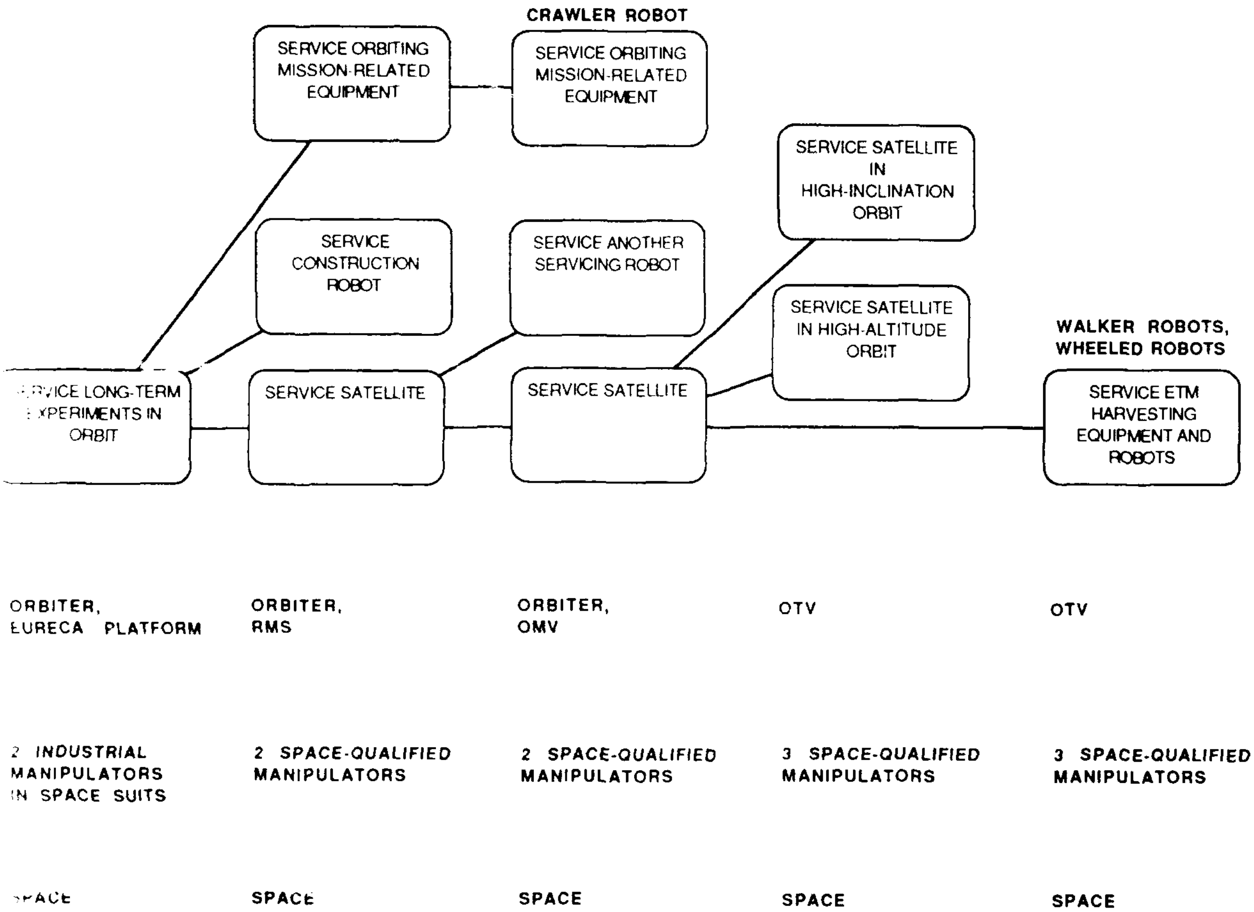


Figure 4 Servicing R&D Plan

- Use of off-the-shelf mechanisms, such as industrial robots and grippers.
- Minimal modification of hardware.
- Control algorithms in software.

3.1.4 Servicing Demonstrations

The first demonstration in the plan in Figure 4 is to verify that the servos in an industrial robot can move the robot accurately in zero gravity on a stable platform. The second verifies that two arms mounted on a free platform can operate without dynamic instability. The third demonstrates, in a pressurized module on a sounding rocket, effective methods for handling objects in zero gravity and adequate performance of an industrial robot arm. This is illustrated in Figure 5.

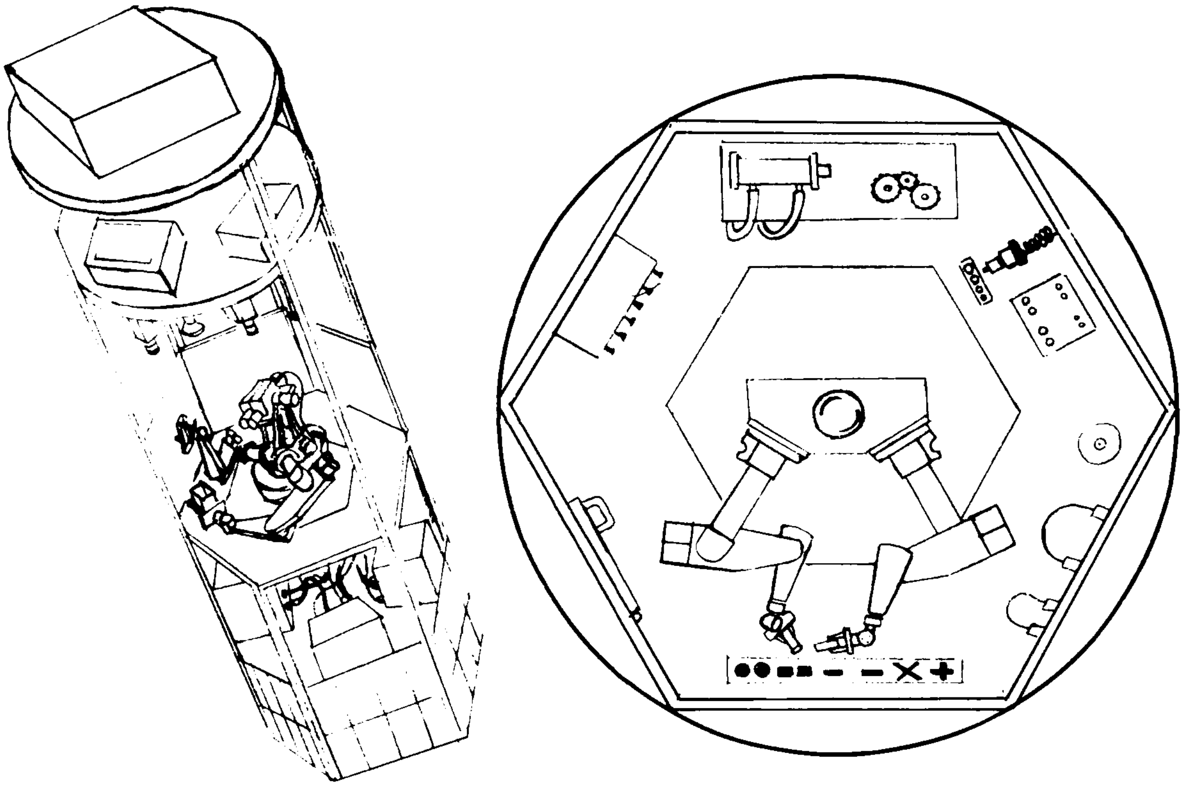


Figure 5 Demonstration of an Industrial Robot in Zero Gravity

The fourth demonstration is to verify the ability of a robot arm to work in zero gravity and vacuum (although in a space suit). The fifth verifies the ability of two robot arms to service experiment packages on a free platform deployed from the orbiter for extended periods. The sixth verifies capture and servicing, in proximity to the orbiter, of mission-related equipment in orbit, construction robots, and a nonrotating satellite, using the remote manipulator

system (RMS) for mobility. The seventh demonstrates an ability to capture and service mission-related equipment in orbit, other servicing robots, and a slowly rotating satellite, in the vicinity of the orbiter, using the orbital maneuvering vehicle (OMV) for mobility. Eighth is to capture and service rapidly rotating satellites in orbits that cannot be obtained by the orbiter. The last demonstration verifies an ability to service equipment used for transporting and harvesting ETM.

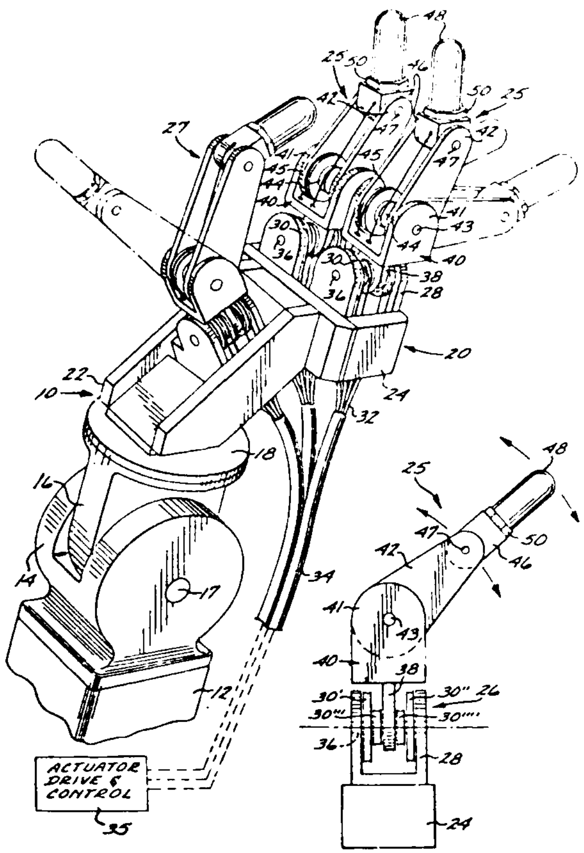
3.1.5 Dexterity Development Plan

Dexterity of future robots for servicing and construction is especially important and can be achieved by means of a mechanical hand or its equivalent. The dexterity that will be needed for autonomous robots in space will require

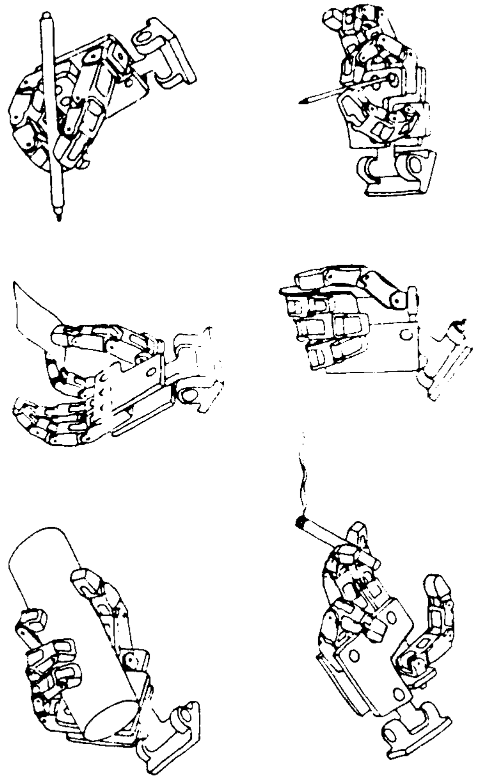
- Increasing sensitivity of sensors
- Increasing fusion of multisensory information
- Wider bandwidth coupling between sensors and effectors
- Finer motions
- Increasingly "intelligent" high-level control
- More sophisticated hands.

Two experimental hands, representative of the best current technology, are illustrated in Figure 6. The three-fingered hand in Figure 6(a) is the Stanford-JPL hand and the four-fingered hand in Figure 6(b) is the Utah-MIT hand. *Both of these hands are candidates* for use in space, redesigned for space but retaining the same basic design and performance. They may demonstrate more dexterity in space than an astronaut with his hand in a space-suit glove. For a specific job, a special tool may be more effective than an anthropomorphic hand. However, a hand is a good universal tool and can hold special purpose tools. In Figure 7, a future, dexterous robot is shown making electrical repairs. Figure 8, a copy of an adversitement by Fairchild, illustrates a future, dexterous robot repairing another robot.

A plan for developing the needed dexterity is shown in Figure 9. Key technological advances are indicated along the top row, with consequent applications derived downwards. The applications increase in complexity from the use of low-reation-force hand tools (such as the reactionless torque wrench that NASA developed for astronauts to use in EVA) to the disassembly of physically damaged equipment. As in the case of the plan in Figure 4 for servicing R&D, the plan spans a period of more than one decade (from the present to about the year 2001) and many other supporting developments and intermediate goals will be necessary. However, the establishment and maintenance of such a plan serves to establish priorities for R&D and ensure that all of the needed technology will be available for each step in the creation of useful robots in space.



(a) Stanford-JPL Hand
[Source: M. T. Mason and J. K. Salisbury, Jr.
Robot Hands and the Mechanics of Manipulation,
p. 81, (MIT Press, Cambridge, Massachusetts, 1985).]



(b) Utah-MIT Hand
[Source: S. C. Jacobsen, E. K. Iversen, D. F. Knutti, R. T. Johnson,
and K. B. Biggers, "Design of the Utah/M.I.T. Hand,"
*Proceedings 1986 IEEE International Conference
on Robotics and Automation*,, Vol. 3, p. 1521
(San Francisco, April 1986).]

Figure 6 Two Experimental Mechanical Hands

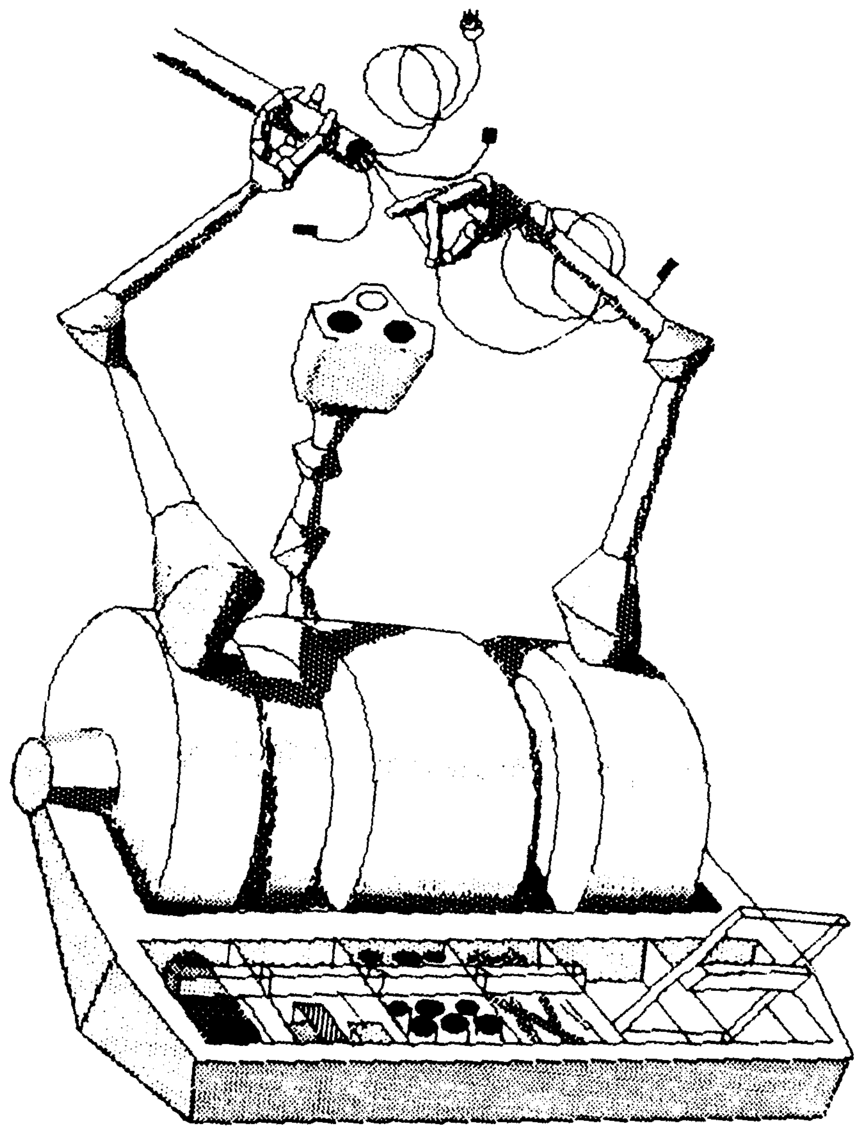


Figure 7 Medium-sized Repair Robot

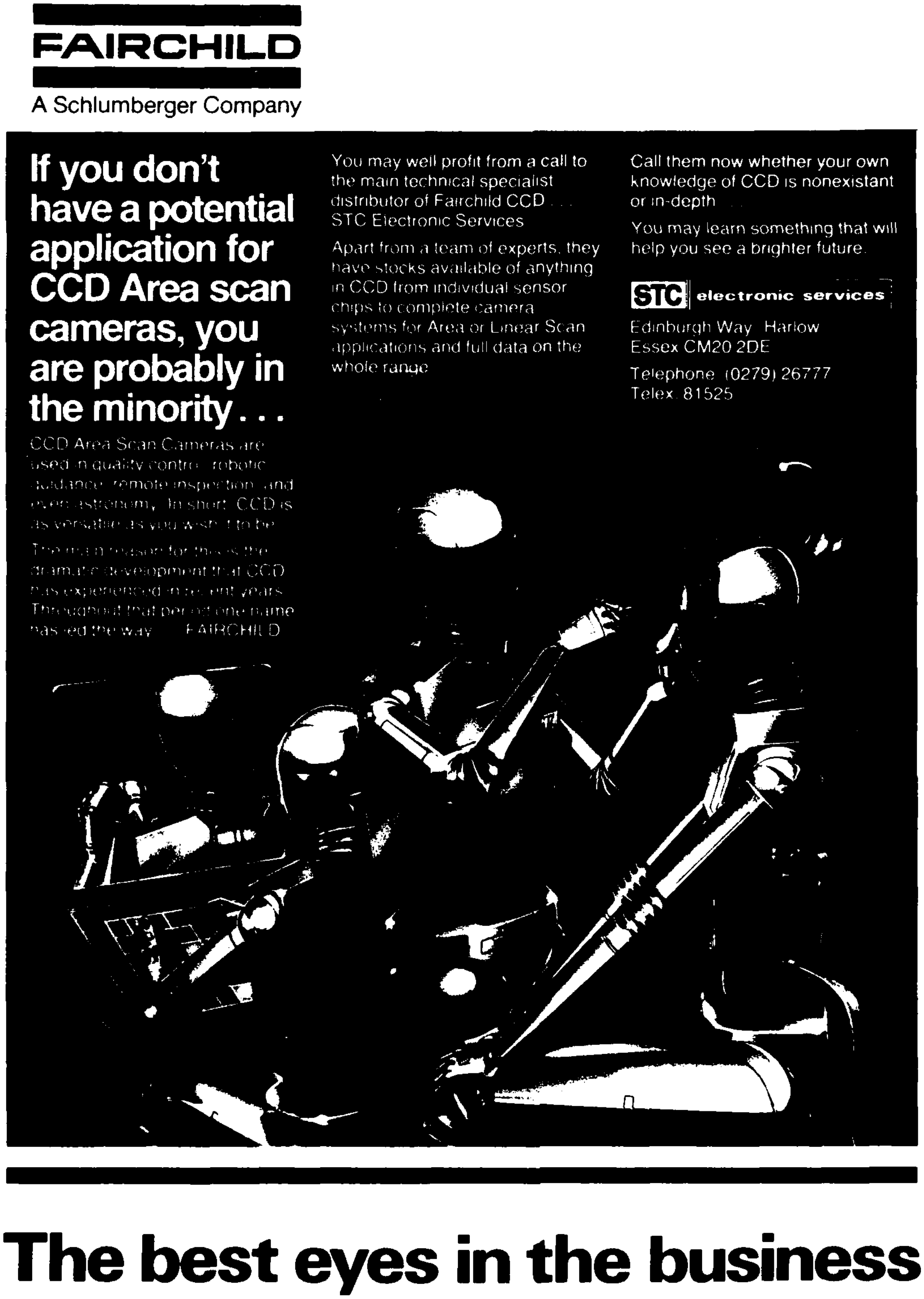
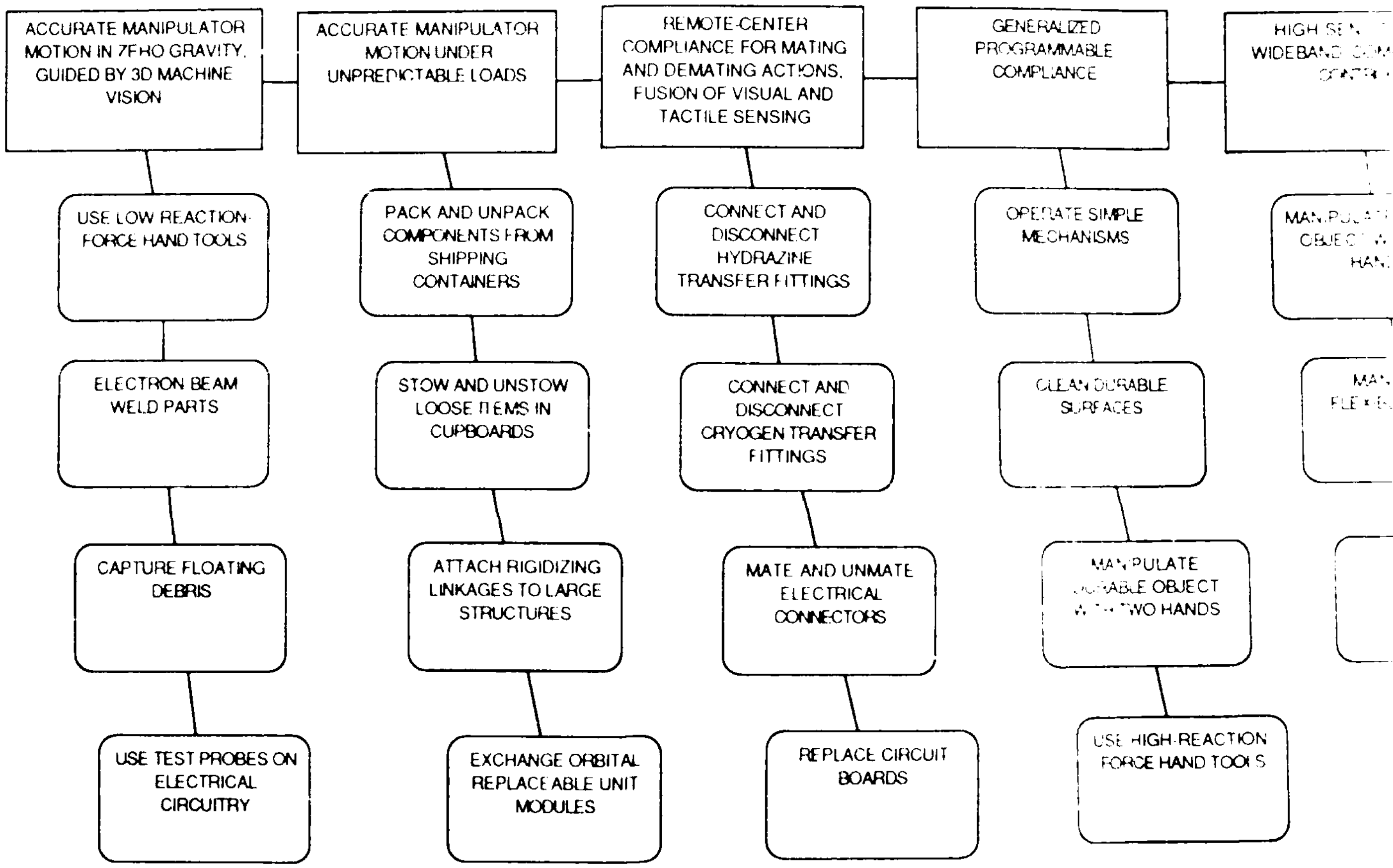
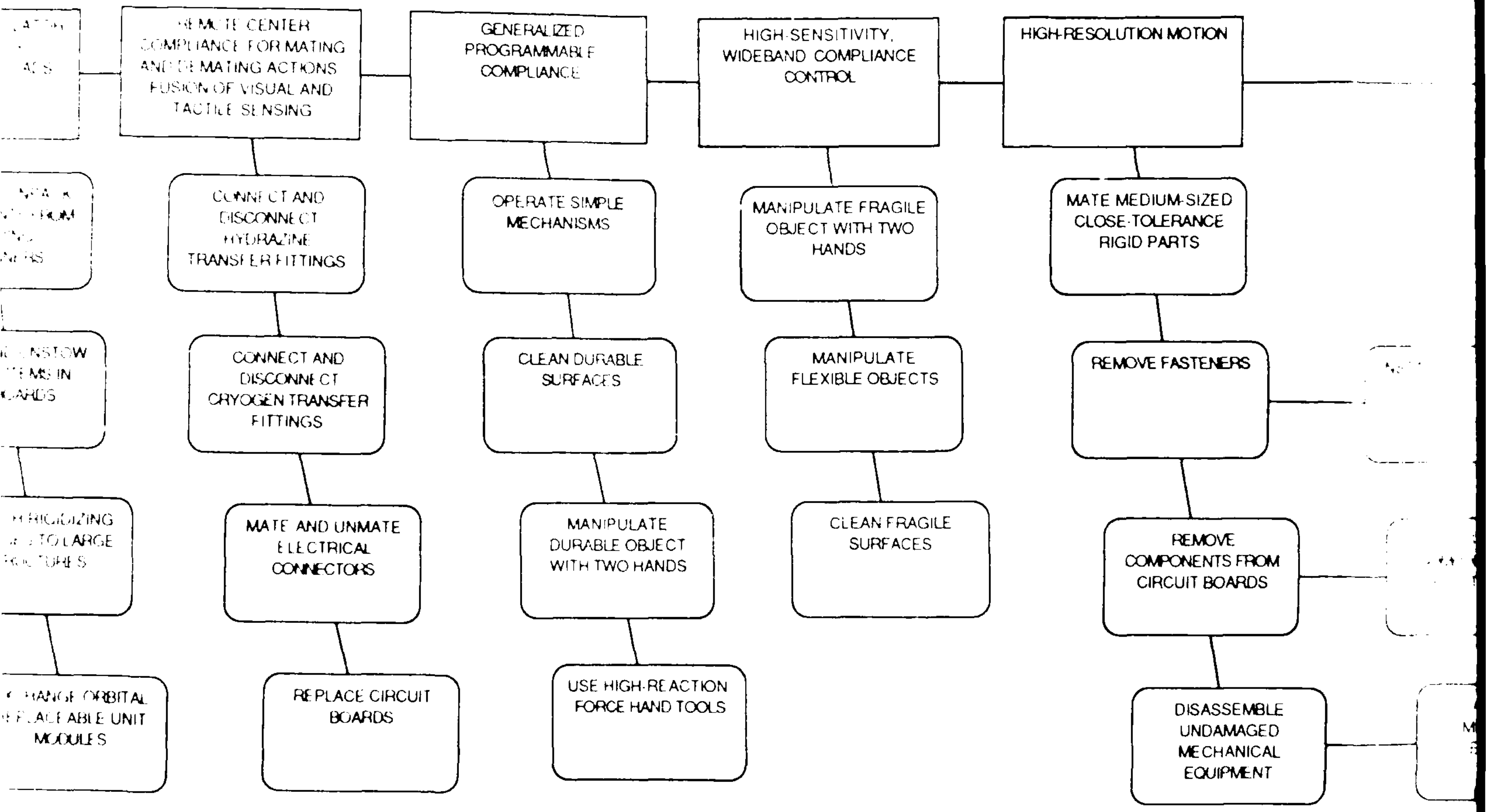


Figure 8 A Robot Repairing Another Robot
[Source: *The Industrial Robot*, Vol 10, No. 4, inside front cover (December 1983).]


ACCURATE MANIPULATOR MOTION IN ZERO GRAVITY, GUIDED BY 3D MACHINE VISION
USE LOW REACTION-FORCE HAND TOOLS
ELECTRON BEAM WELD PARTS
CAPTURE FLOATING DEBRIS
USE TEST PROBES ON ELECTRICAL CIRCUITRY
ACCURATE MANIPULATOR MOTION UNDER UNPREDICTABLE LOADS
PACK AND UNPACK COMPONENTS FROM SHIPPING CONTAINERS
STOW AND UNSTOW LOOSE ITEMS IN CUPBOARDS
ATTACH RIGIDIZING LINKAGES TO LARGE STRUCTURES
EXCHANGE ORBITAL REPLACEABLE UNIT MODULES
REMOTE-CENTER COMPLIANCE FOR MATING AND DEMATING ACTIONS, FUSION OF VISUAL AND TACTILE SENSING
CONNECT AND DISCONNECT HYDRAZINE TRANSFER FITTINGS
CONNECT AND DISCONNECT CRYOGEN TRANSFER FITTINGS
MATE AND UNMATE ELECTRICAL CONNECTORS
REPLACE CIRCUIT BOARDS
GENERALIZED PROGRAMMABLE COMPLIANCE
OPERATE SIMPLE MECHANISMS
CLEAN DURABLE SURFACES
MANIPULATE DURABLE OBJECT WITH TWO HANDS
USE HIGH-REACTION FORCE HAND TOOLS



REMOTE CENTER COMPLIANCE FOR MATING AND DEMATING ACTIONS FUSION OF VISUAL AND TACTILE SENSING
GENERALIZED PROGRAMMABLE COMPLIANCE
HIGH-SENSITIVITY, WIDEBAND COMPLIANCE CONTROL
HIGH-RESOLUTION MOTION
CONNECT AND DISCONNECT HYDRAZINE TRANSFER FITTINGS
OPERATE SIMPLE MECHANISMS
MANIPULATE FRAGILE OBJECT WITH TWO HANDS
MATE MEDIUM-SIZED CLOSE-TOLERANCE RIGID PARTS
CONNECT AND DISCONNECT CRYOGEN TRANSFER FITTINGS
CLEAN DURABLE SURFACES
MANIPULATE FLEXIBLE OBJECTS
REMOVE FASTENERS
MATE AND UNMATE ELECTRICAL CONNECTORS
MANIPULATE DURABLE OBJECT WITH TWO HANDS
CLEAN FRAGILE SURFACES
REMOVE COMPONENTS FROM CIRCUIT BOARDS
CHANGE ORBITAL REPLACEABLE UNIT MODULES
REPLACE CIRCUIT BOARDS
USE HIGH-REACTION FORCE HAND TOOLS
DISASSEMBLE UNDAMAGED MECHANICAL EQUIPMENT

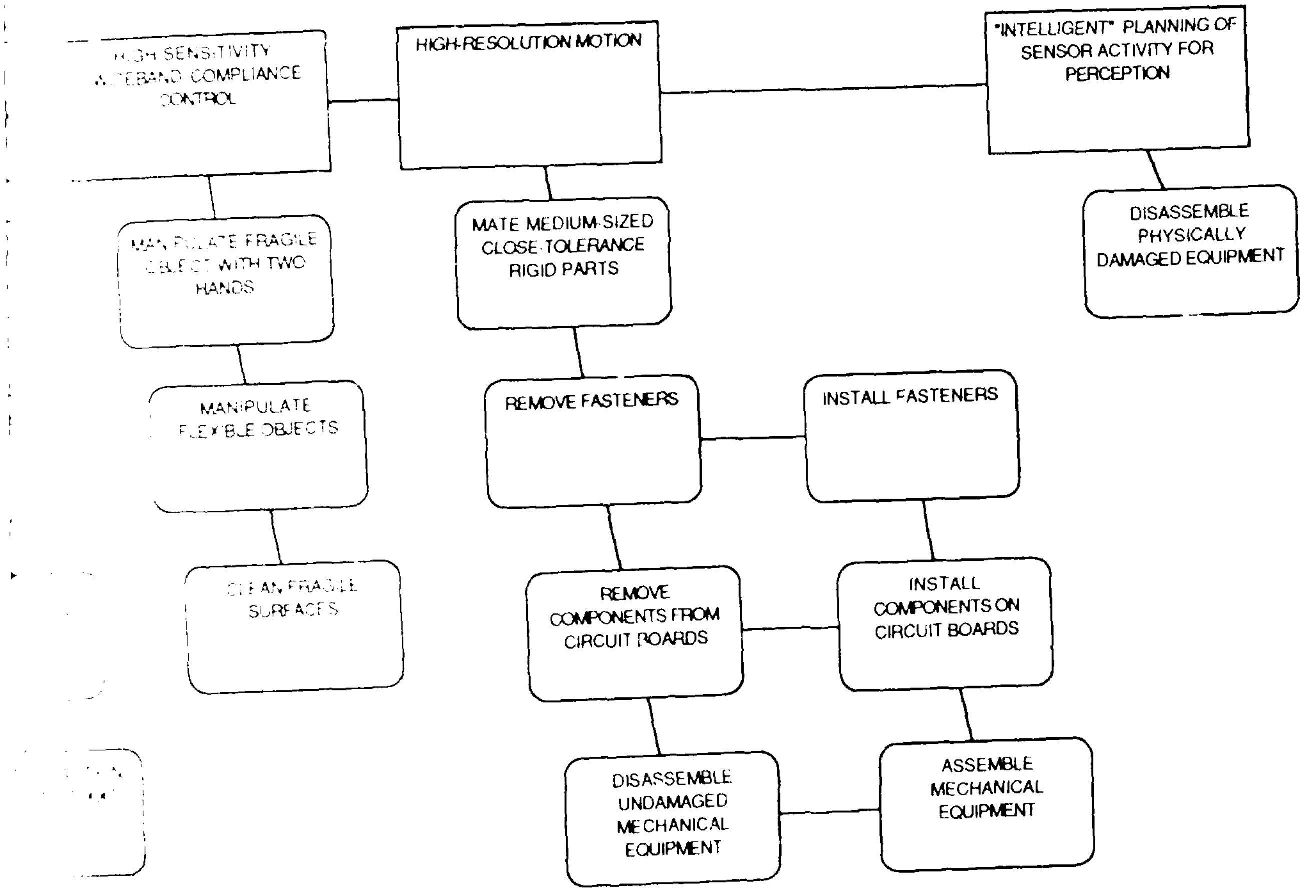


Figure 9 Dexterity Plan

3.1.6 Representative Construction Demonstrations

A series of demonstrations *in space* of *autonomous* construction robots might address tasks such as the following, in order of increasing difficulty:

- Erect a large, not very rigid structure.
- Install equipment on such a structure with "easy" fasteners.
- Manipulate a large object with two arms acting together and grasping it at opposite ends.
- Handle nonrigid materials.
- Bend material to a required shape when it has unpredictable springback.
- Use non-debris-producing power tools.

In Figure 10, a plan for construction of large structures in orbit is shown in a larger context, and spans a period that extends beyond the year 2007, when a program to obtain ETM for construction might be in operation. The plan for construction of large structures in orbit begins with three separate activities: (1) a forecast of future capabilities in automation and robotics (A&R), (2) definition of future military requirements for large structures in space, and (3) research on processes for forming simulated extraterrestrial materials (SETM) in zero gravity. Like the plans in Figures 4 and 9, this plan would yield useful capabilities before reaching the final goal noted in the plan.

3.1.7 RMS-attached Robots

A remote-manipulator system such as the RMS on the orbiter or a mobile RMS (MRMS) can provide a limited amount of mobility to a robot attached to it. Advantages of this arrangement are that it

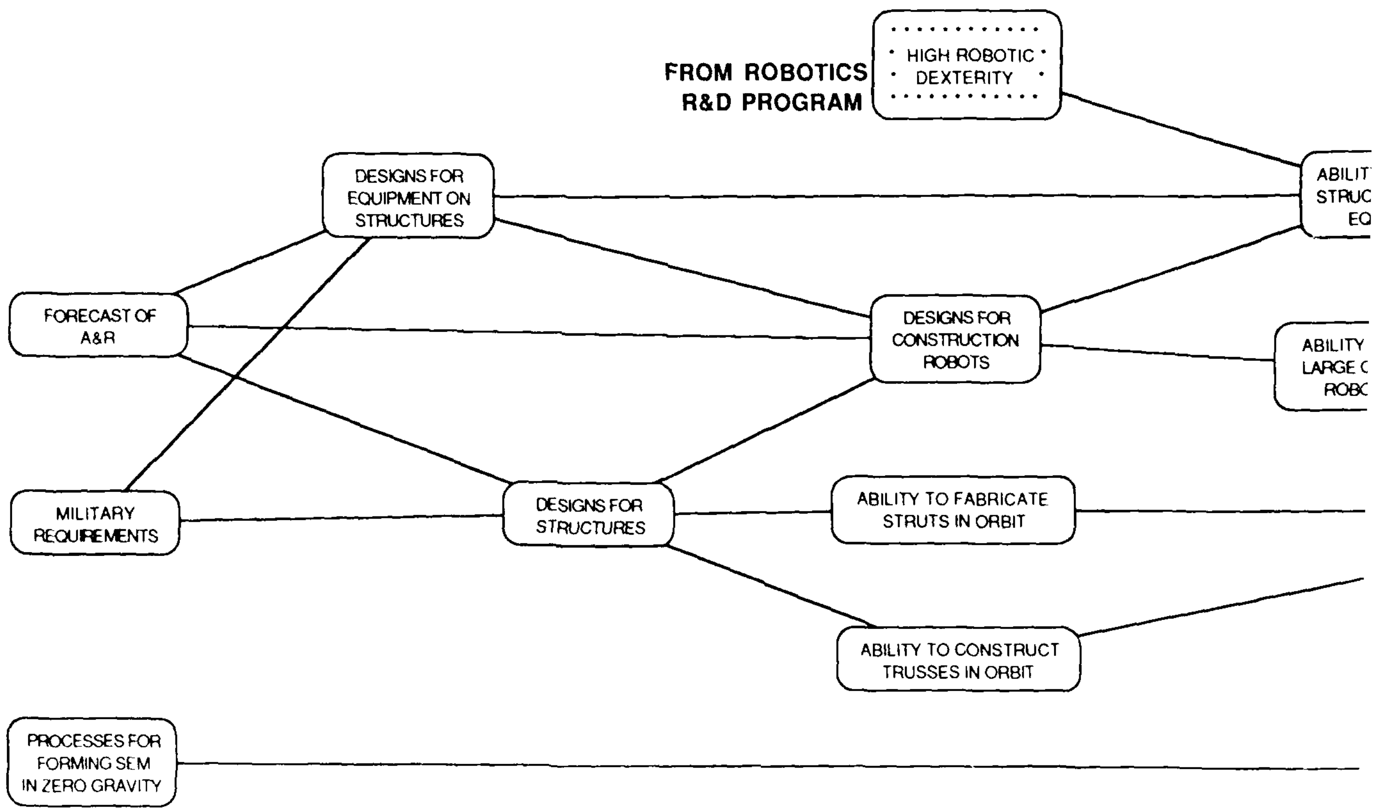
- Does not consume reaction mass.
- Is lower cost than a free-flyer.
- Allows access to the exterior of the orbiter or structure for repairs.
- Can serve as a test bed for control system development for

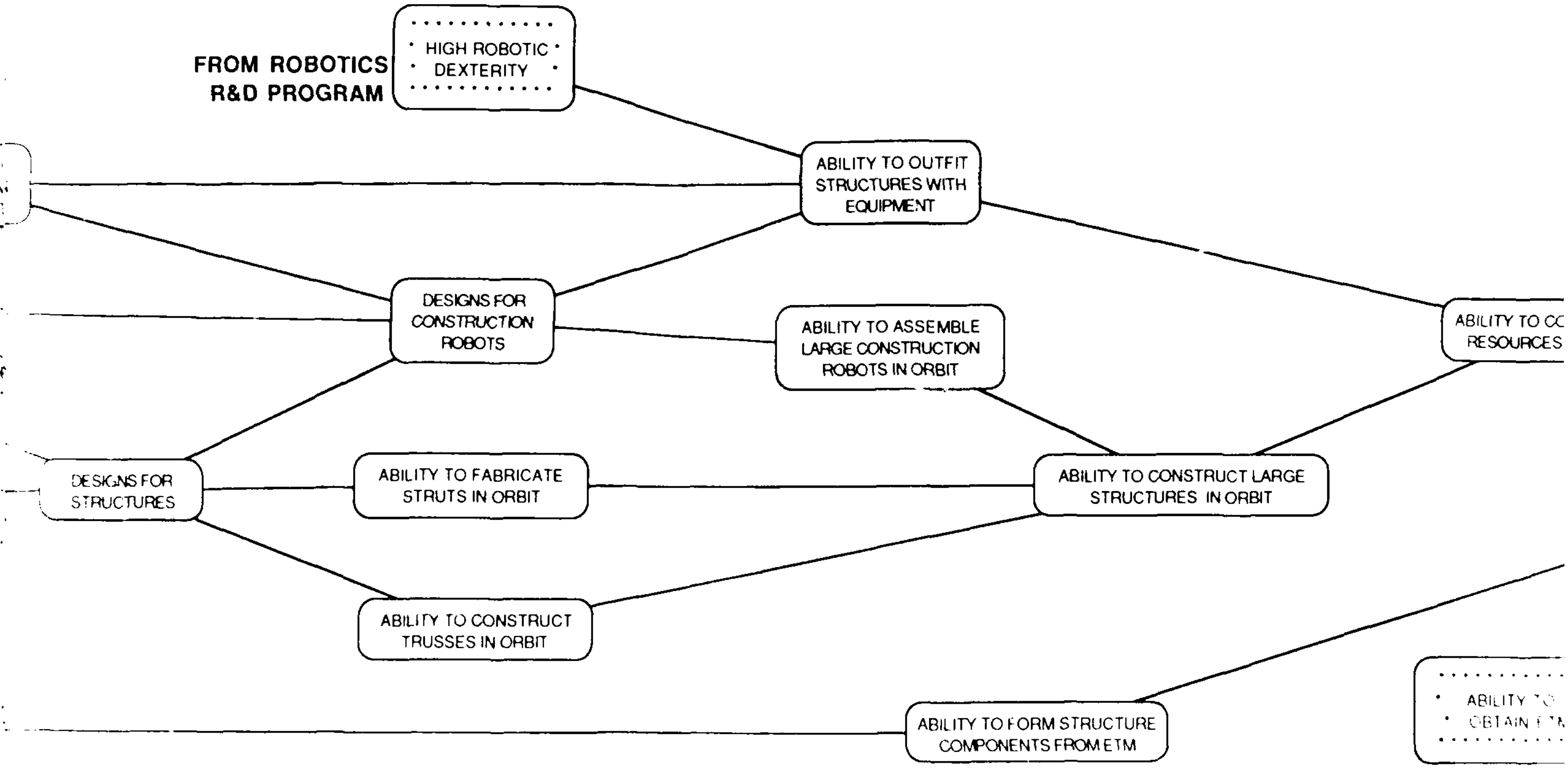
  -Proximity operations such as satellite capture.
  -Dynamic stability of the RMS-robot-satellite system.
  -Man-machine interfaces for programming robot travel.
  -Displacement of the robot by inertial and reaction forces during manipulation.

- Does not require that the satellite be brought into the orbiter's bay.

- Allows the robot to work on space vehicles or structures that are too large to fit in the bay.

- Can grapple a stabilized satellite (but not a spinning one).


FROM ROBOTICS R&D PROGRAM
HIGH ROBOTIC DEXTERITY
DESIGNS FOR EQUIPMENT ON STRUCTURES
FORECAST OF A&R
DESIGNS FOR CONSTRUCTION ROBOTS
MILITARY REQUIREMENTS
DESIGNS FOR STRUCTURES
ABILITY TO FABRICATE STRUTS IN ORBIT
ABILITY TO CONSTRUCT TRUSSES IN ORBIT
PROCESSES FOR FORMING SEM IN ZERO GRAVITY



FROM ROBOTICS R&D PROGRAM
HIGH ROBOTIC DEXTERITY
ABILITY TO OUTFIT STRUCTURES WITH EQUIPMENT
DESIGNS FOR CONSTRUCTION ROBOTS
ABILITY TO ASSEMBLE LARGE CONSTRUCTION ROBOTS IN ORBIT
DESIGNS FOR STRUCTURES
ABILITY TO FABRICATE STRUTS IN ORBIT
ABILITY TO CONSTRUCT LARGE STRUCTURES IN ORBIT
ABILITY TO CONSTRUCT TRUSSES IN ORBIT
ABILITY TO FORM STRUCTURE COMPONENTS FROM ETM

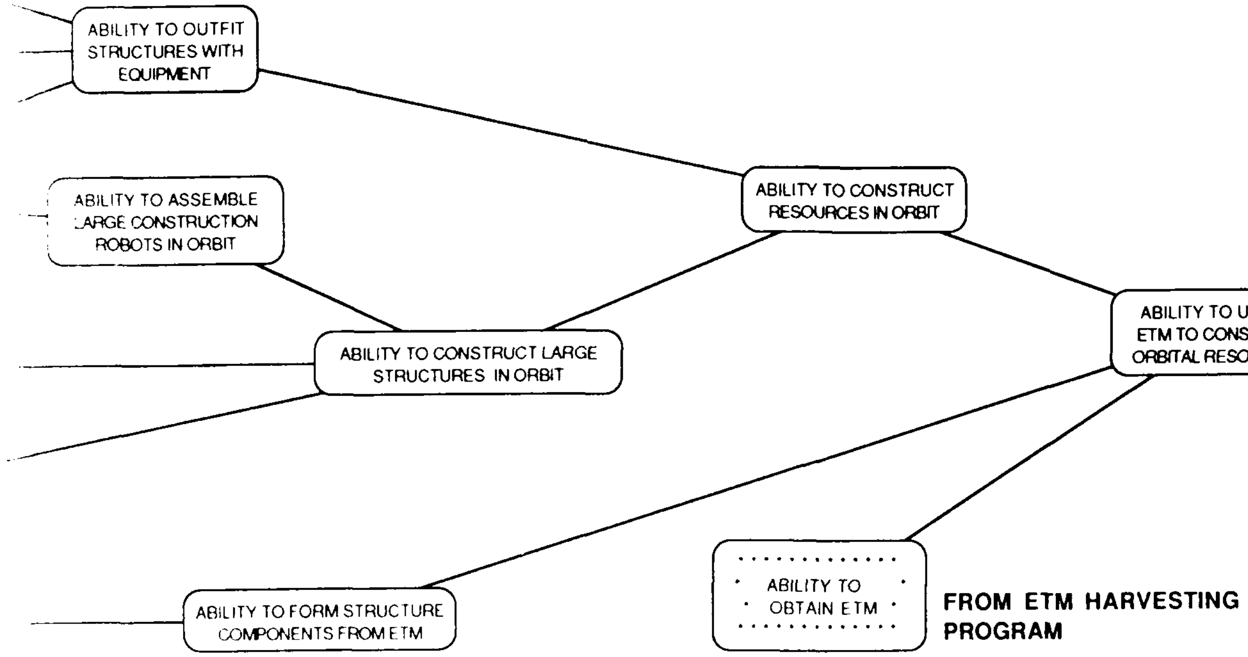


Figure 10 Plan for Construction of Large Structures in Orbit

3.1.8 Unattached "Crawler" Robots

Unattached robots that can move about by walking or crawling on some other structure have more mobility than attached robots, and other advantages:

- Does not consume reaction mass

- Can reach interior of structures

- Does not require dedicated equipment on structure for mobility

- Can cross gaps between structures.

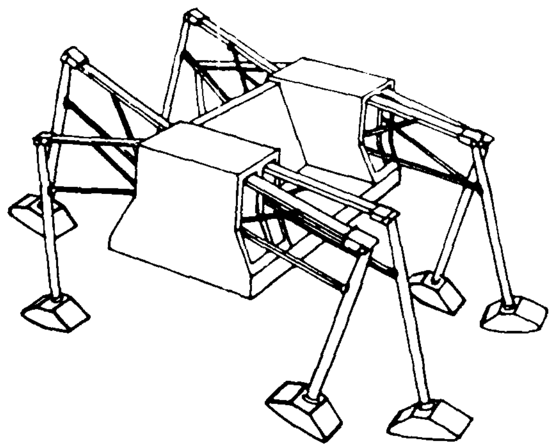
Some experimental walking robots are illustrated in Figure 11. The eight-legged robot in Figure 11(a) is the Iron Mule Train developed by Aerojet General Corporation. The four-legged robot in Figure 11(b) is the ODEX I, developed by Odetics Inc. The other four-legged robot, in Figure 11(c) is the PV II developed by S. Hirose and others at the Tokyo Institute of Technology. The Adaptive Suspension Vehicle (ASV), developed by R. B. McGee and his coworkers at Ohio State University is illustrated in Figure 11(d). These vehicles, of course, are not designed for weightless space. However, the control software required for legged mobility is directly applicable to crawler robots in space. A future crawler robot is illustrated in Figure 12.

3.1.9 Free-flying Robots

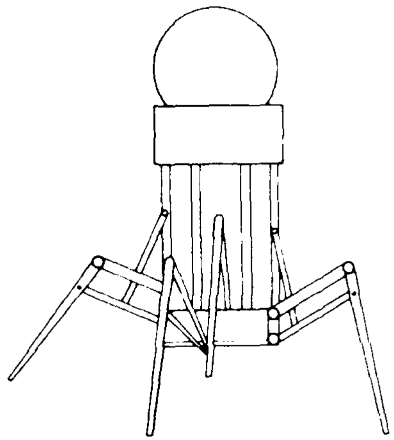
Free-flying robots can work on structures that are not strong enough to absorb reaction forces of a walker or RMS. Operations in the vicinity of another spacecraft such as the space station require benign plumes (OMV). Remote operations require high energy propulsion [Orbital Transfer Vehicle (OTV)]. A combination of OMV and OTV may be useful for remote servicing.

Free-flying robots can deliver services where people cannot go because of high radiation orbits at high inclination angles or high altitudes or a need to work on unsafe weapons, fueled vehicles, active station-keeping platforms, or malfunctioning platforms.

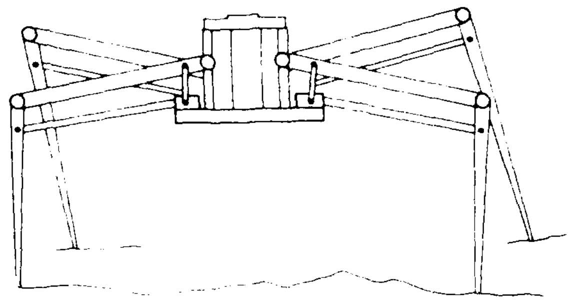
Techniques will be needed for compensation of motion caused by reaction forces in free-flying robots. Figure 13 shows a free flyer proposed by Boeing, Future free flyers are illustrated in Figures 14 and 15.



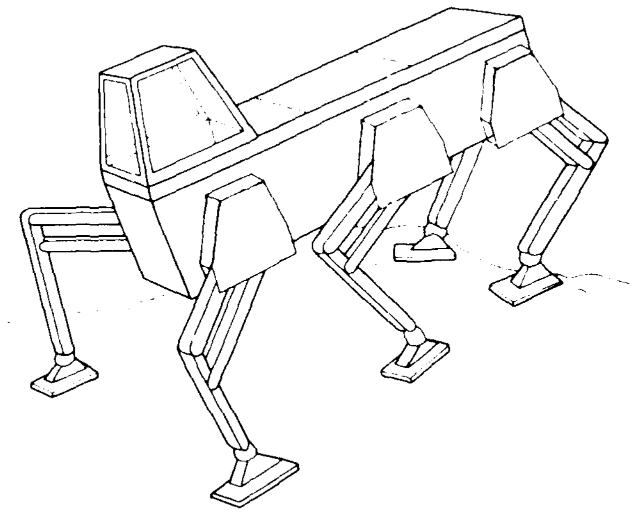
(a) Irɔn Mule Train



(b) ODEX I



(c) PV II



(d) ASV

Figure 11 Experimental Walking Robots
[Source: D. J. Todd, *Walking Machines: an Introduction to Legged Robots*, pp. 17, 152, 161 (Chapman and Hall, New York, 1985).]

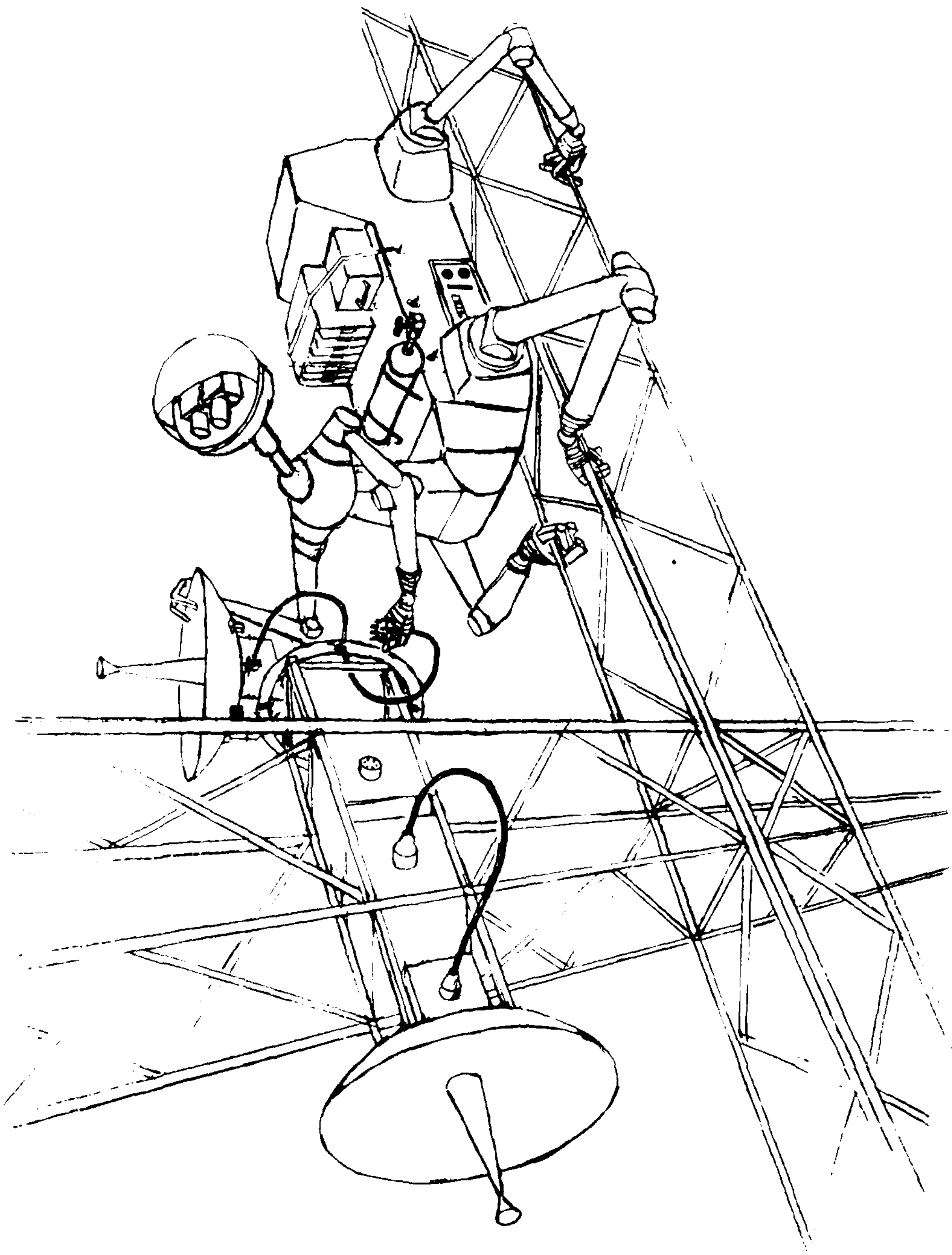


Figure 12 Future Crawling Robot

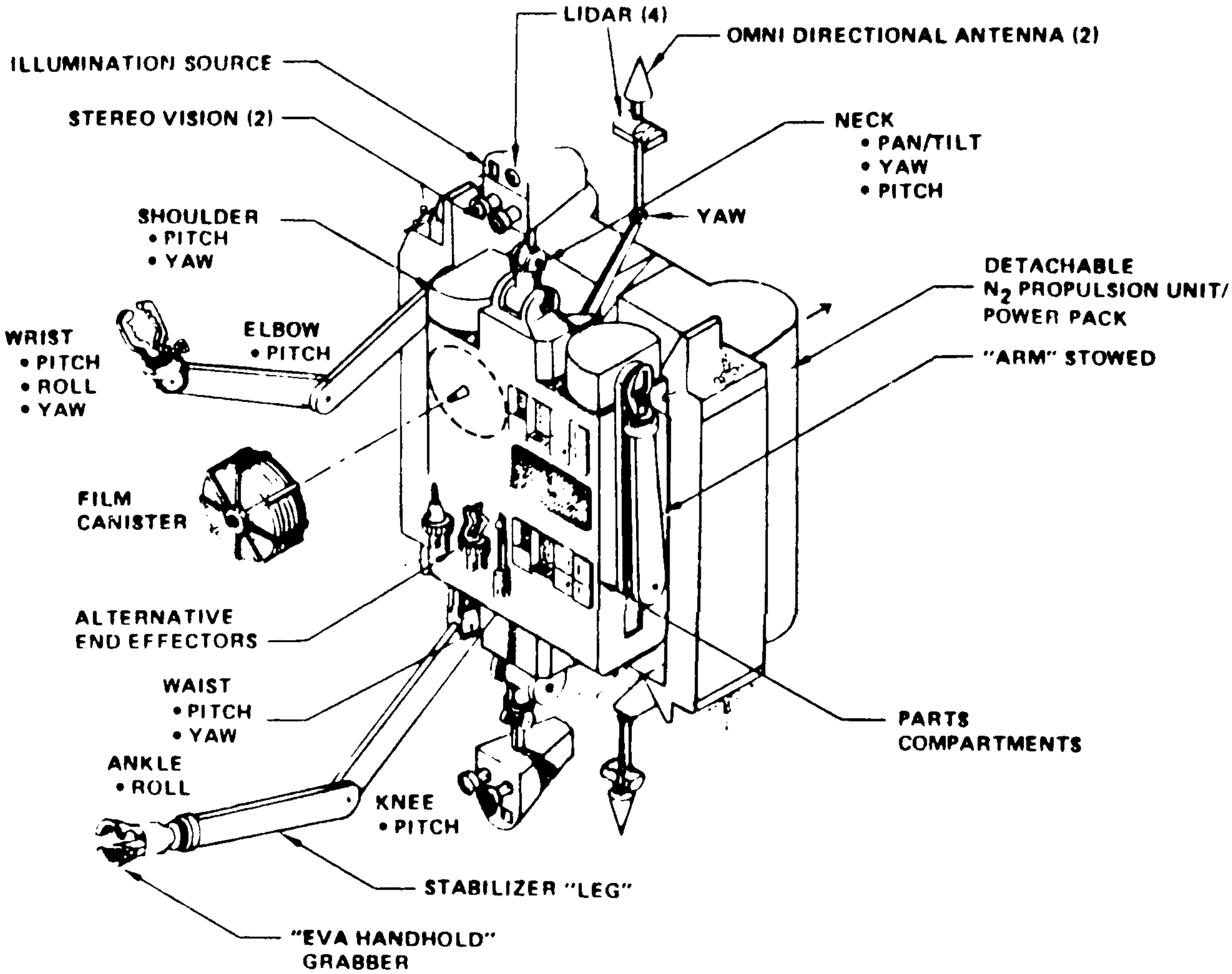


Figure 13 Boeing Extravehicular Robot Concept
[Source: "Space Station Automation and Robotics Study," p. 2-6, Final Report, Operator-Systems Interface, Boeing Aerospace Company and Boeing Computer Services Company (November 1984).]

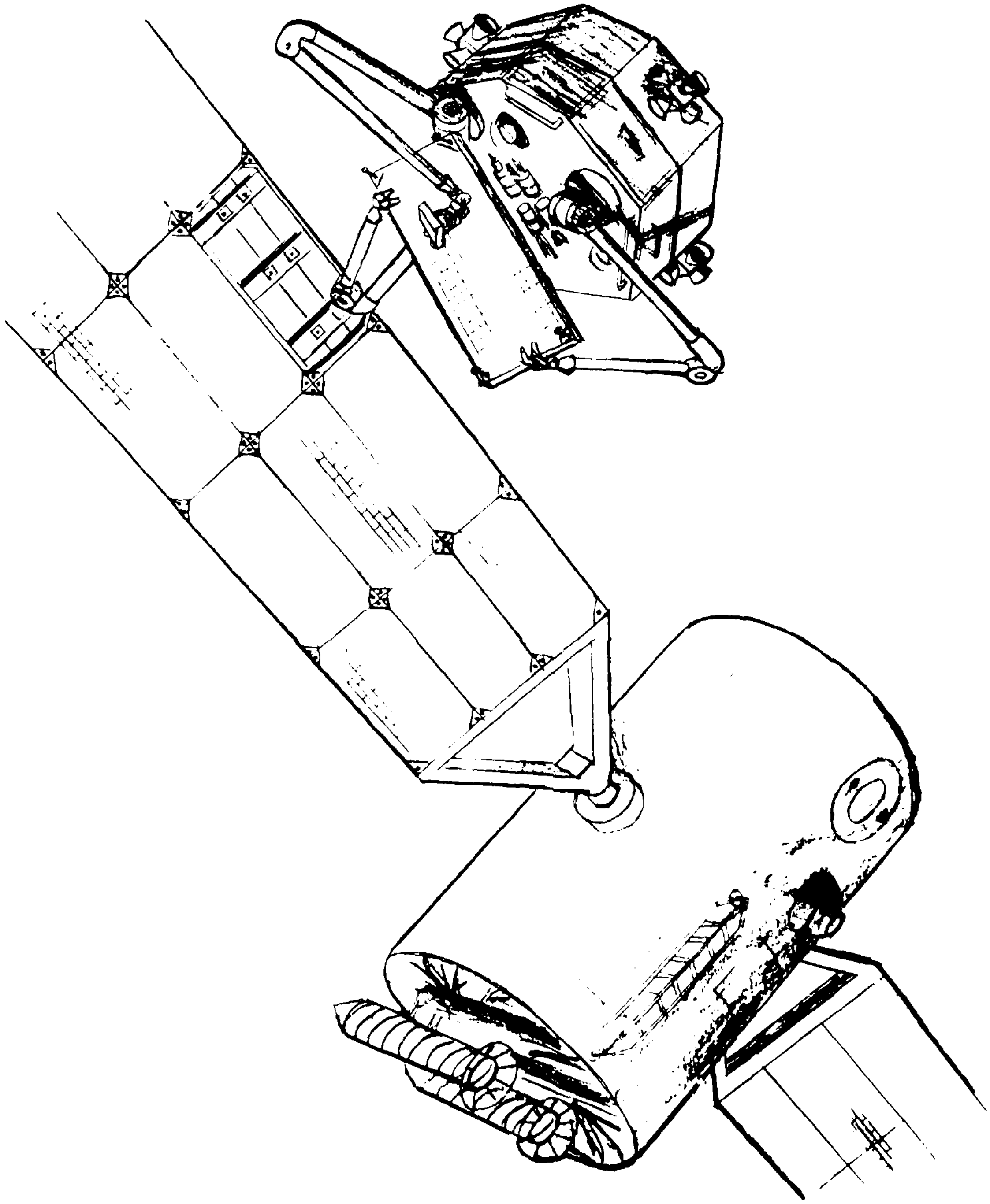


Figure 14 A Free-flying Construction Robot

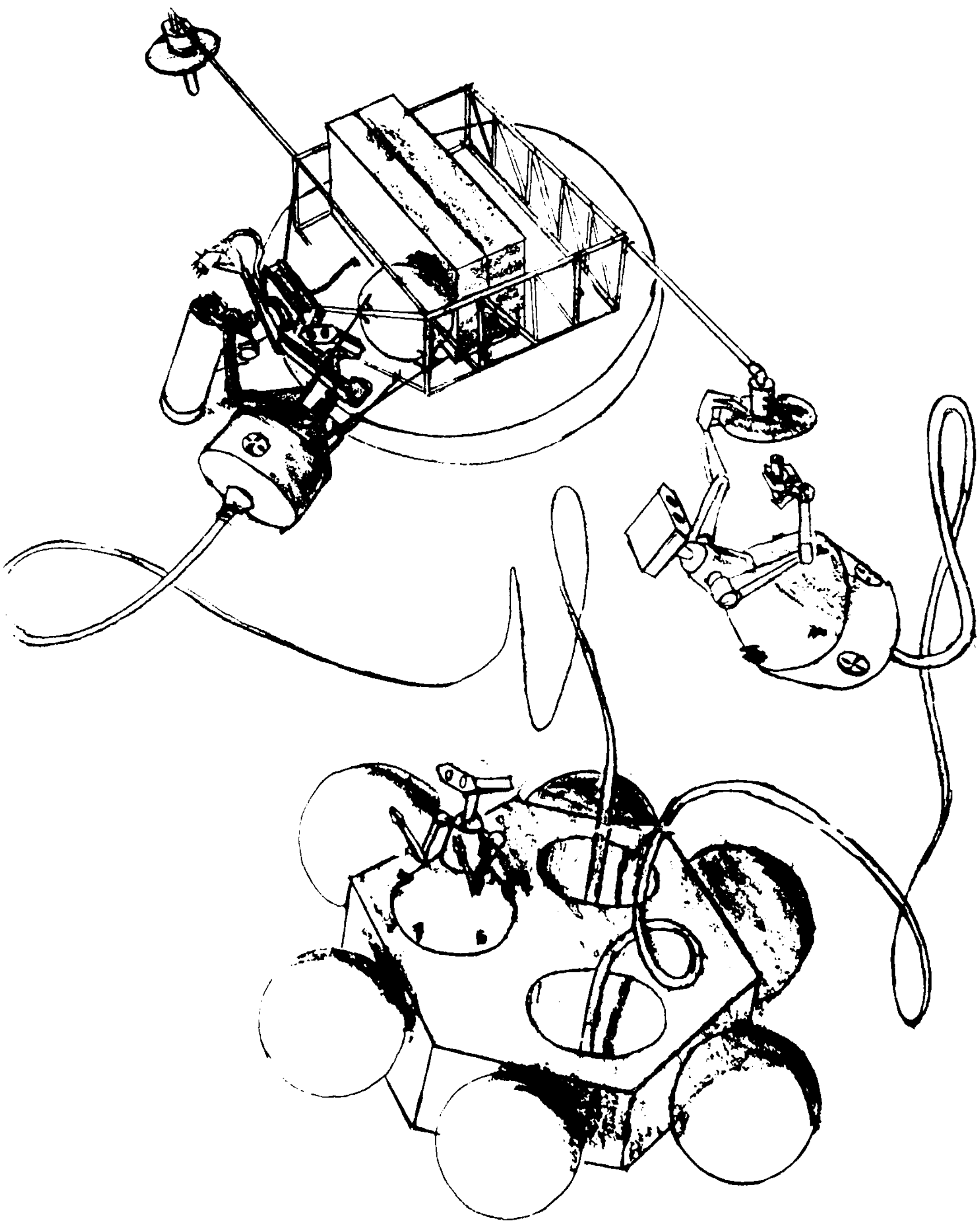


Figure 15 Future OTV and Two Free-flying Repair Robots

3.1.10 Technology Drivers in Automated Servicing

Some of the requirements that are evident for future robots that can be used in servicing and construction in space will pull the technology. These robots must

- Be easy to program by high-level task descriptions.
- Produce their own detailed low-level sensor and effector action plans automatically.
- React effectively to unexpected events.
- Operate correctly and reliably.
- Diagnose faults in electrical, mechanical, optical, hydraulic, and thermal-control equipment.
- Have mobility and be able to guide themselves.
- Have access to multikilowatt power sources.

3.2 Ground Manufacturing

The use of robotics in ground manufacturing of spacecraft, launch vehicles, and payloads is important for reducing the cost of placing man-made (or robot-made) objects in space. A manufacturing R&D plan is shown in Figure 16. It illustrates a broad and comprehensive approach to automation, taking into account the interactions between designs for automated manufacturing, automated launch, and automated servicing. The goal, as noted in the right-most box of the plan, is complete automation of the manufacture and launch of space vehicles. An imtermediate goal is a fully automated manufacturing process.

3.2.1 Critical Issues

Some of the technical objectives are to

- Design the launch vehicle for compatibility with automatic manufacturing and launch methods.
- Automate individual manufacturing processes.
- Automate transportation to and from launch site.
- Automate launch site integration activities.
- Automate the launch procedure.

3.2.2 Design for Automated Manufacture

In designing methods for automating the manufacture of spacecraft, and the like, the first step should be to study manual manufacturing methods, determining the materials, components, and manufacturing processes used. This can be followed by an analysis of the choices of materials, components, and processes, and identification of alternatives.

A new design for automated manufacture should be prepared, based on the old design, retaining necessary features. The following activities would take place in an iterative design cycle:

- Design a standardized, simplified launch vehicle suitable for automated manufacture.
- Identify build/buy decisions in the design. Some components may be obtainable "off-the-shelf."
- Identify major "build" processes.
- Select the optimum combination of production methods, considering hard automation, flexible automation, and possible manual procedures.
- Develop a detailed manufacturing-process plan, plant layout, designs for automated equipment, requirements for robots, and automatically guided vehicles.

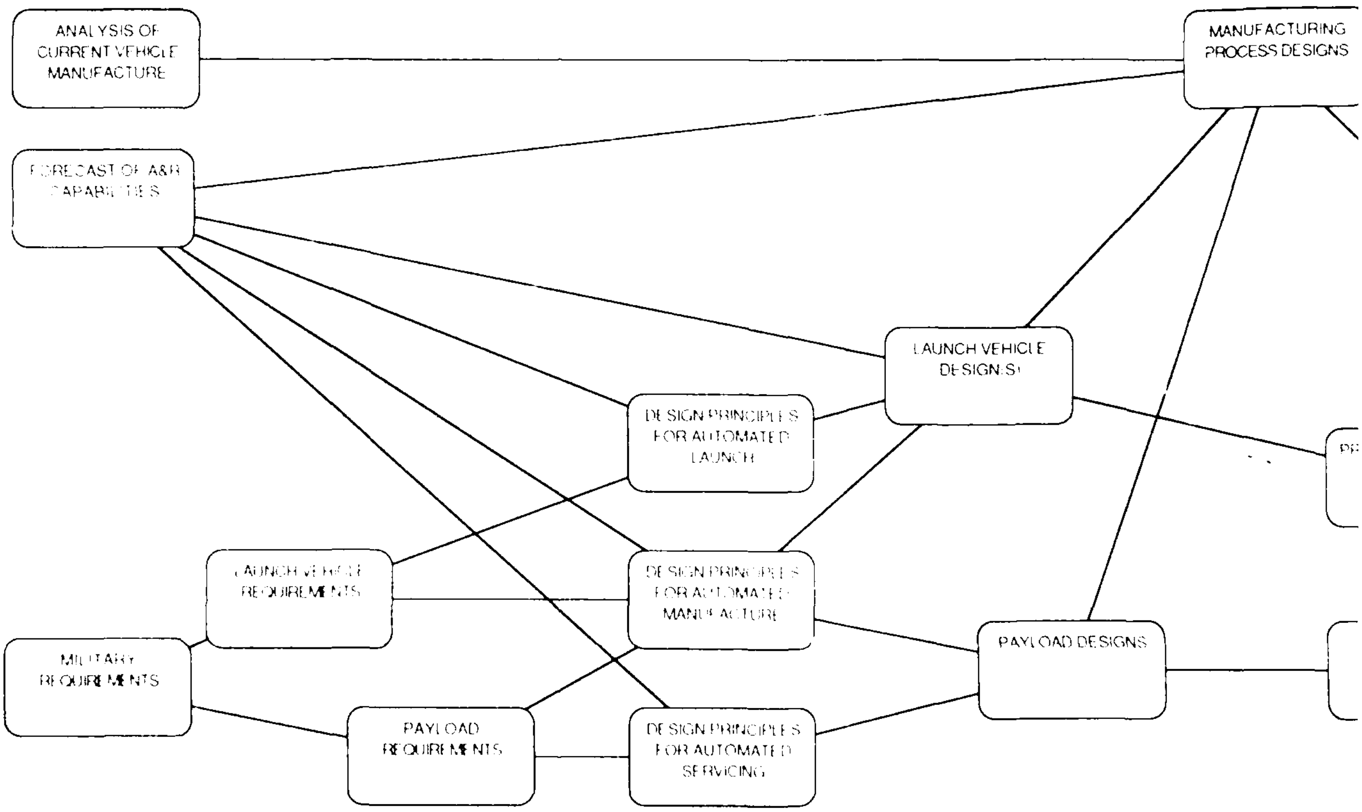
After several iterations, select an optimal combination of vehicle and plant designs. An automated manufacturing facility is illustrated in Figure 17.

3.2.3 Proofs of Concepts and Demonstrations of Specific Manufacturing Processes

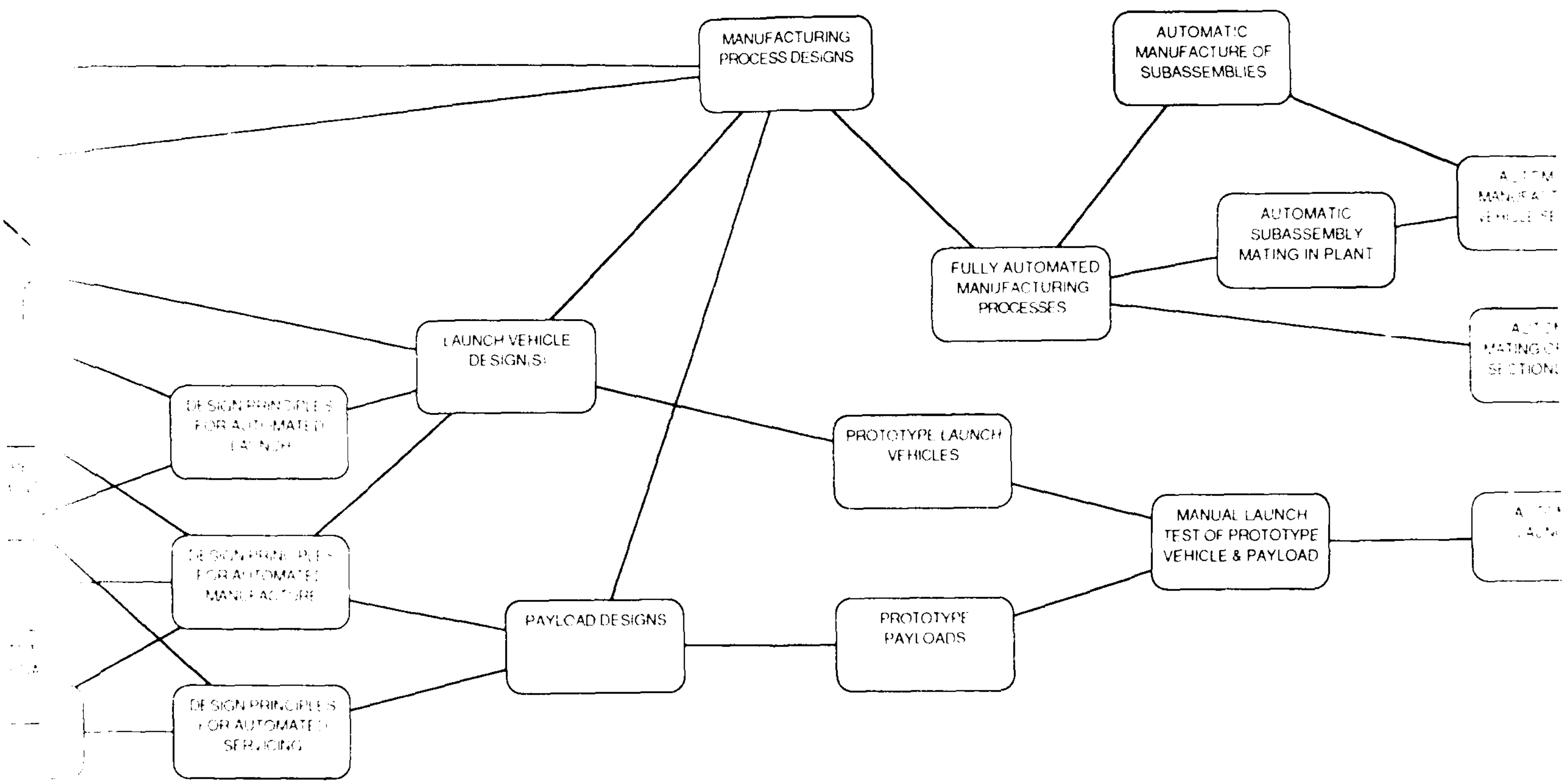
Many specific manufacturing processes are being automated by industry in general, and some of this automation can be used directly in manufacturing for space, but in other cases, special or unique processes may be necessary and call for proofs of concept and demonstrations before they can be integrated into the manufacturing process. Specific manufacturing processes that should be considered for further development to make them useful for space manufacturing include sheet metal forming, riveting, arc welding, drilling and tapping, gluing and sealing, pipe bending, assembly, inspection, and functional testing.

3.2.4 Automatic Construction of Major Subassemblies

The building of major subassemblies for space vehicles and payloads will require attention to sheet metal assemblies, tanks, piping, electrical cable harnesses, hoses, electronics/guidance systems/computers. hydraulic systems, solid rocket motors, liquid rocket motors, and turbo machinery.



ANALYSIS OF CURRENT VEHICLE MANUFACTURE
MANUFACTURING PROCESS DESIGNS
FORECAST OF A&R CAPABILITIES
LAUNCH VEHICLE DESIGN(S)
DESIGN PRINCIPLES FOR AUTOMATED LAUNCH
LAUNCH VEHICLE REQUIREMENTS
DESIGN PRINCIPLES FOR AUTOMATED MANUFACTURE
MILITARY REQUIREMENTS
PAYLOAD DESIGNS
PAYLOAD REQUIREMENTS
DESIGN PRINCIPLES FOR AUTOMATED SERVICING



MANUFACTURING PROCESS DESIGNS
AUTOMATIC MANUFACTURE OF SUBASSEMBLIES
AUTOMATIC SUBASSEMBLY MATING IN PLANT
FULLY AUTOMATED MANUFACTURING PROCESSES
LAUNCH VEHICLE DESIGN(S)
DESIGN PRINCIPLES FOR AUTOMATED LAUNCH
PROTOTYPE LAUNCH VEHICLES
MANUAL LAUNCH TEST OF PROTOTYPE VEHICLE & PAYLOAD
DESIGN PRINCIPLES FOR AUTOMATED MANUFACTURE
PAYLOAD DESIGNS
PROTOTYPE PAYLOADS
DESIGN PRINCIPLES FOR AUTOMATED SERVICING

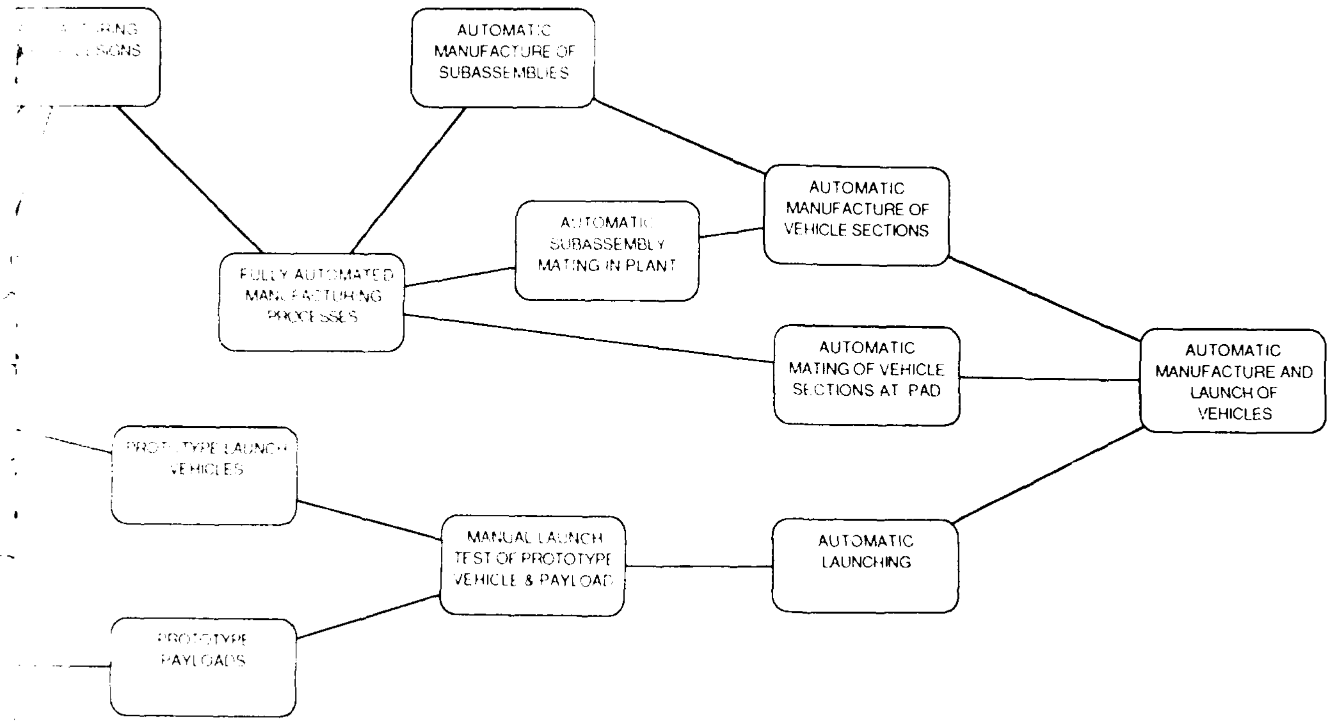


Figure 16 Manufacturing R&D Plan

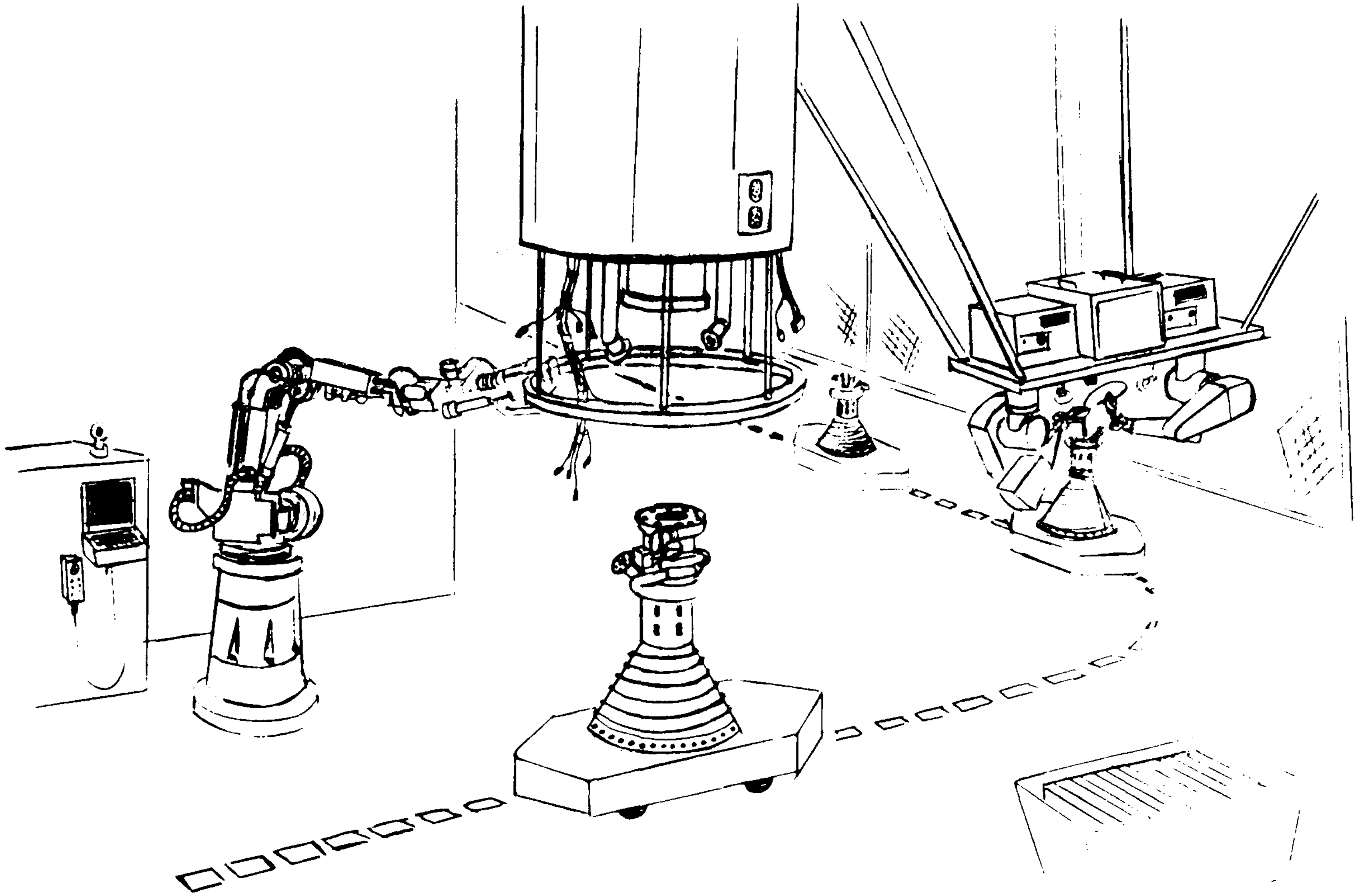


Figure 17 An Automated Manufacturing Facility

3.2.5 Demonstration of Integrated, Automated Manufacture and Launch

Finally, the automatic manufacture of a complete space vehicle can be demonstrated, including the assembly of the major parts in the factory and the mating of stages and payloads at the launch site.

3.3 Extraterrestrial Material Harvesting

The harvesting of ETM, although a very-long-term objective, is included as a part of the overall plan for military robotics in space because of the future need for large mass and large structures in space, and the inherent economy of using material that is more readily available because it is in a shallower gravity well. The use of lunar material, and martian material, for processing and manufacturing are discussed in the report of the National Comission on Space, for example [*Pioneering the Space Frontier*, (May 1986)]. Automated harvesting of ETM is illustrated in Figure 18 and a plan for harvesting ETM is shown in Figure 19. It includes early earth-based development using simulated ETM (SETM), and the development of concepts for transportation, harvesting (mining), and the products that would be made from ETM.

3.3.1 Critical Issues

Some of the critical issues for development of a capability for harvesting extraterrestrial material are

- Find out how to form and work ETM by experimentation with simulated ETM on the ground.

- Design the ETM extraction, transport, and end-use equipment as an integrated system, so that many items can be built largely from ETM, and so that, after an intial investment, the harvesting rate can grow exponentially with only minimal additional investment.

- Establish a small pilot plant at the chosen harvesting site for verification of the technology before committing to a growth program.

3.3.2 Ground Demonstrations

Before significant quantities of ETM are available, earth-based development can be undertaken:

- Melt and form simulated extraterrestrial material (SETM) into pellets and then into structural components (first with humans, then robots).

- Automatically repair other robots, mining equipment, forming equipment, and the like.

- Run autonomous mobile robot over lunarlike terrain to show locomotion and navigation.

- Mine some earth dirt that is similar to lunar dirt (possibly in a vacuum for increased realism).

3.3.3 Earth-orbit Demonstrations

Demonstrations in earth orbit can be undertaken next:

- Melt and form SETM pellets into components for shields, structures

- Demonstrate debris-free material processing

- Repair other robots and the forming equipment

- Assemble/form a sections of a shield

- Assemble a section of a structure from components.

3.3.4 Harvesting Site Demonstrations and Operations

Finally, harvesting can be demonstrated at the extraterrestrial site:

- Soft-land unmanned cargo rockets carrying a minimal set of equipment.

- Survey sites for mining, landing, processing, solar collectors.

- Obtain ground truth to verify photographic data about the site.

- Take test borings and analyze samples chemically.

- Mine materials, perhaps several different kinds in different places.

- Physically (not chemically) process materials into pellets and components for structures.

- Construct structures (EML, roads, and shelters)

- Repair other robots, mining, forming, and construction equipment.

3.3.5 Facilities at the Harvesting Site

Facilities at an ETM harvesting site might include a material-processing center, launch facility, landing facility for unmanned cargo, rockets, and visitors, maintenance/laboratory facility, power-generation-and-distribution center, communication-and-control facility, solar furnace, warehouse/storage facilities for unprocessed extraterrestrial material, processed extraterrestrial material, and imported stores.

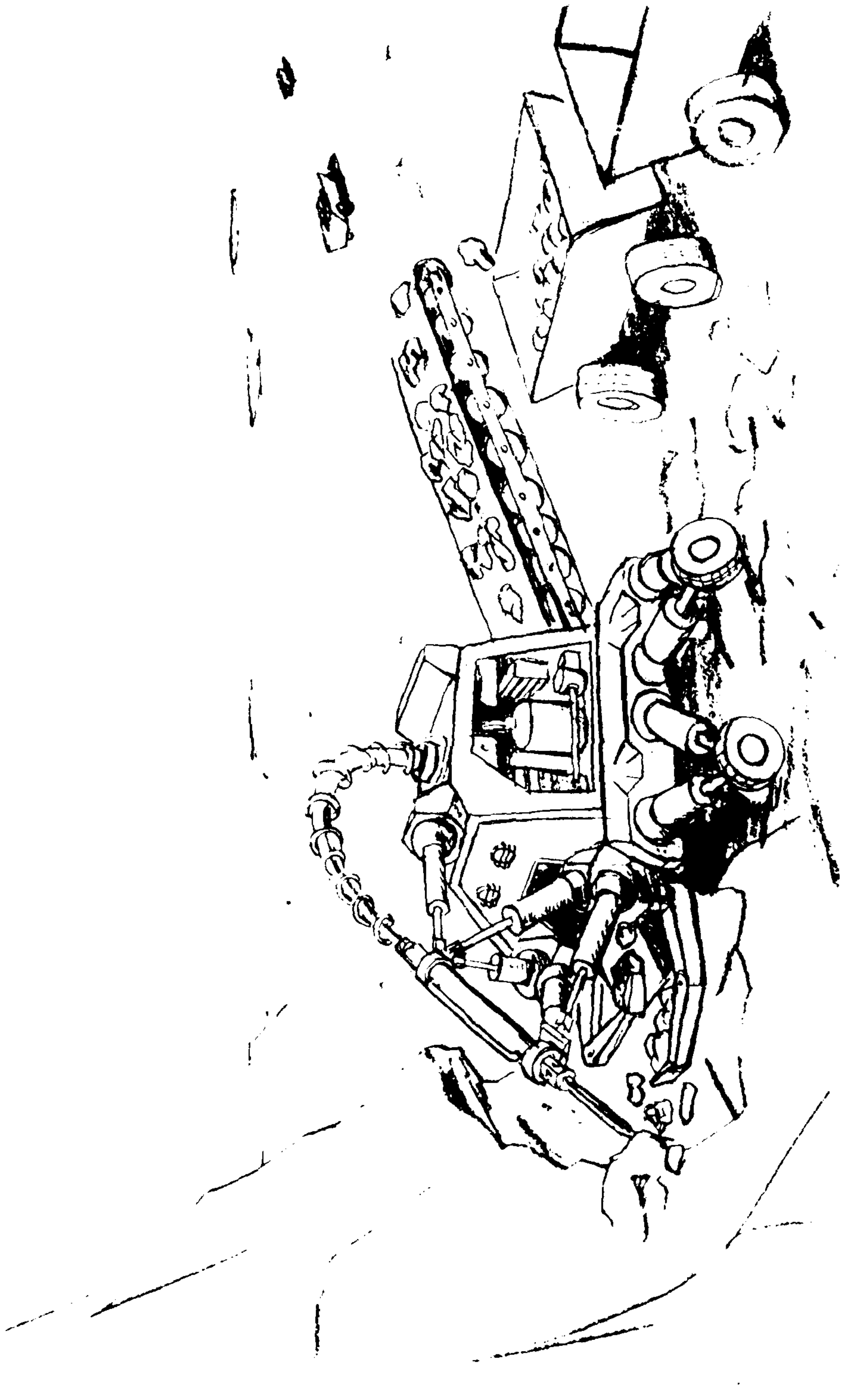
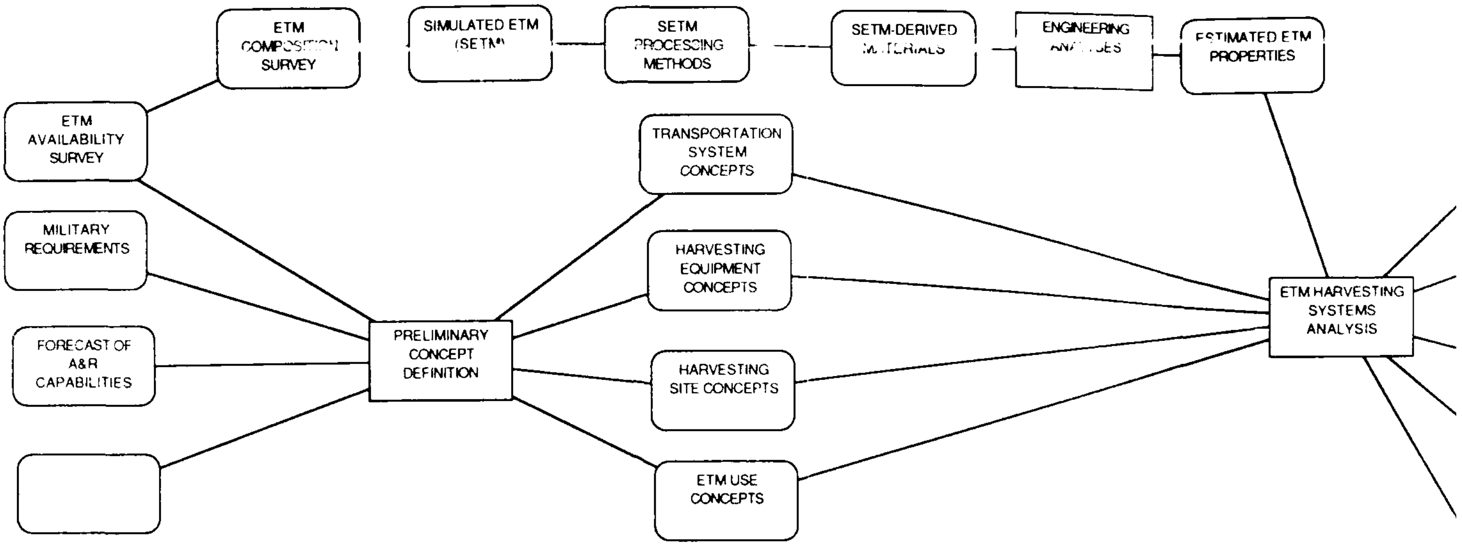
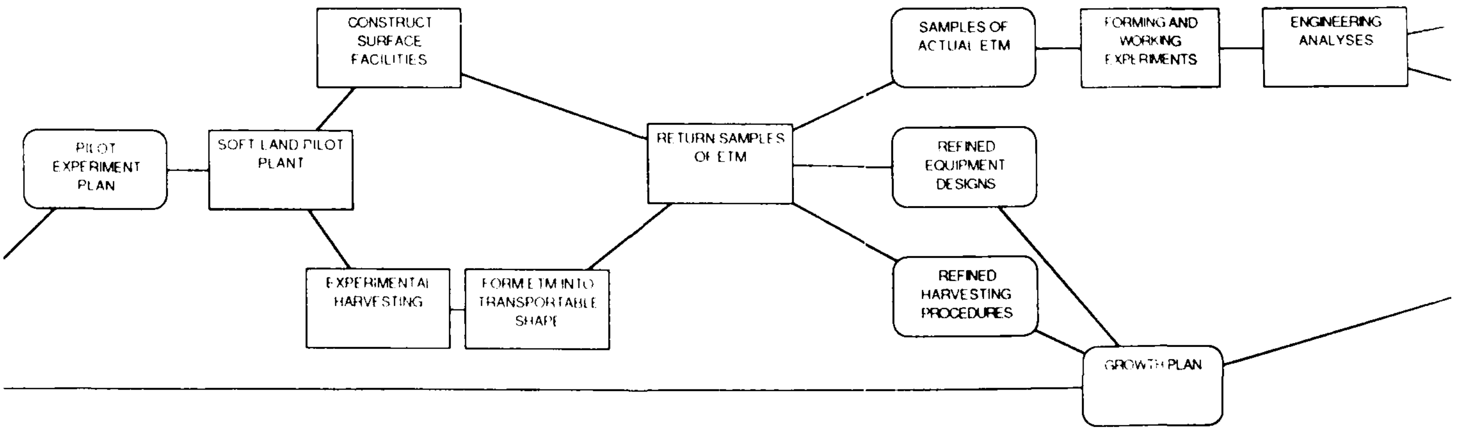


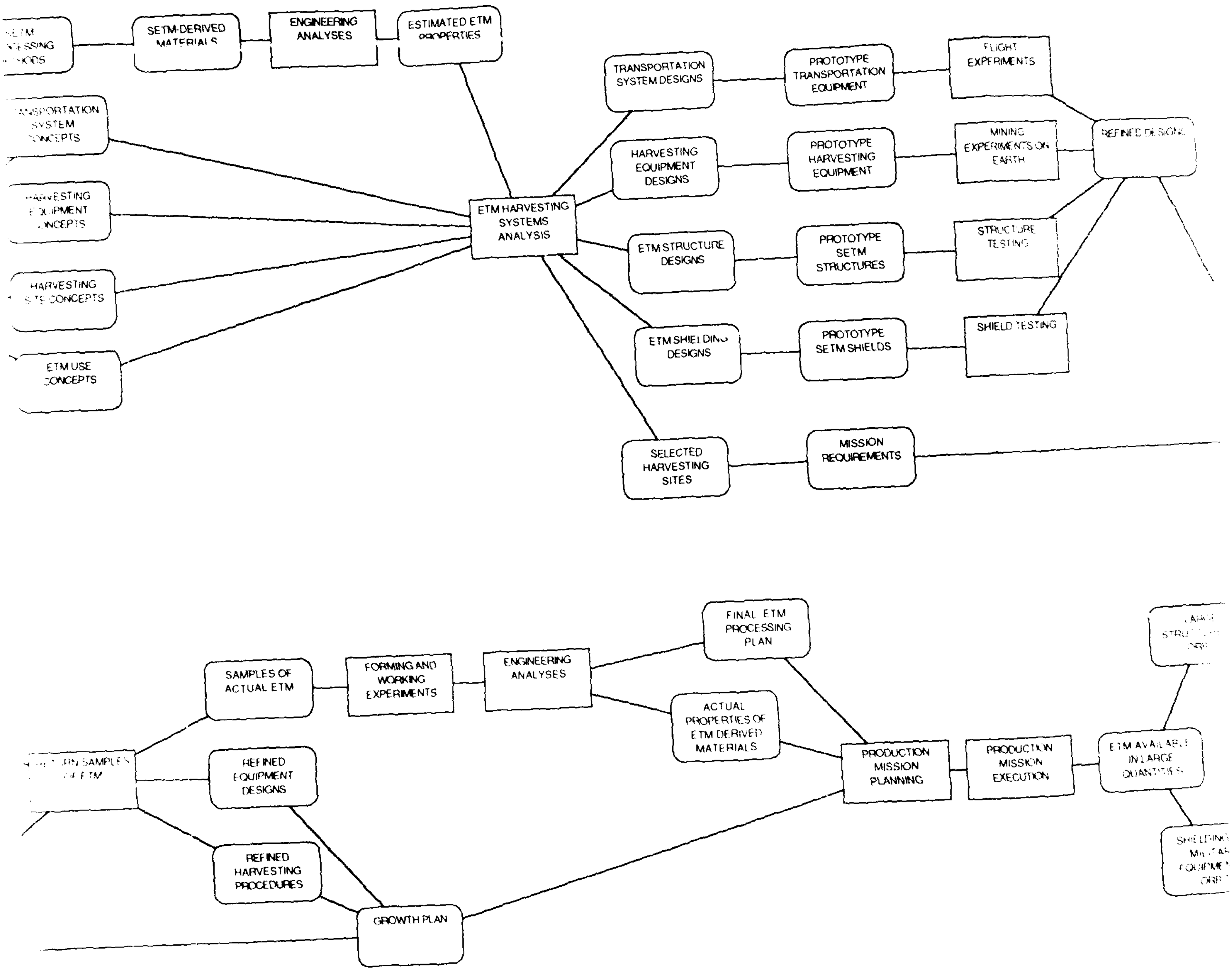
Figure 18 Automated Harvesting of Extraterrestrial Material



ETM
SURVEY
SIMULATED ETM
SETM
PROCESSING
METHODS
SETM-DERIVED
ENGINEERING
PROPERTIES
ETM
AVAILABILITY
SURVEY
TRANSPORTATION
SYSTEM
CONCEPTS
MILITARY
REQUIREMENTS
HARVESTING
EQUIPMENT
CONCEPTS
PRELIMINARY
CONCEPT
DEFINITION
ETM HARVESTING
SYSTEMS
ANALYSIS
FORECAST OF
A&R
CAPABILITIES
HARVESTING
SITE CONCEPTS
ETM USE
CONCEPTS



CONSTRUCT
SURFACE
FACILITIES
SAMPLES OF
ACTUAL ETM
FORMING AND
WORKING
EXPERIMENTS
ENGINEERING
ANALYSES
PILOT
EXPERIMENT
PLAN
SOFT LAND PILOT
PLANT
RETURN SAMPLES
OF ETM
REFINED
EQUIPMENT
DESIGNS
EXPERIMENTAL
HARVESTING
FORM ETM INTO
TRANSPORTABLE
SHAPE
REFINED
HARVESTING
PROCEDURES
PLAN


SETM-DERIVED MATERIALS
ENGINEERING ANALYSES
ESTIMATED ETM PROPERTIES
HARVESTING SITE CONCEPTS
ETM USE CONCEPTS
ETM HARVESTING SYSTEMS ANALYSIS
TRANSPORTATION SYSTEM DESIGNS
PROTOTYPE TRANSPORTATION EQUIPMENT
FLIGHT EXPERIMENTS
HARVESTING EQUIPMENT DESIGNS
PROTOTYPE HARVESTING EQUIPMENT
MINING EXPERIMENTS ON EARTH
ETM STRUCTURE DESIGNS
PROTOTYPE SETM STRUCTURES
STRUCTURE TESTING
ETM SHIELDING DESIGNS
PROTOTYPE SETM SHIELDS
SHIELD TESTING
SELECTED HARVESTING SITES
MISSION REQUIREMENTS
SAMPLES OF ACTUAL ETM
FORMING AND WORKING EXPERIMENTS
ENGINEERING ANALYSES
FINAL ETM PROCESSING PLAN
ACTUAL PROPERTIES OF ETM DERIVED MATERIALS
REFINED EQUIPMENT DESIGNS
REFINED HARVESTING PROCEDURES
GROWTH PLAN
PRODUCTION MISSION PLANNING
PRODUCTION MISSION EXECUTION
ETM AVAILABLE IN LARGE QUANTITIES

Figure

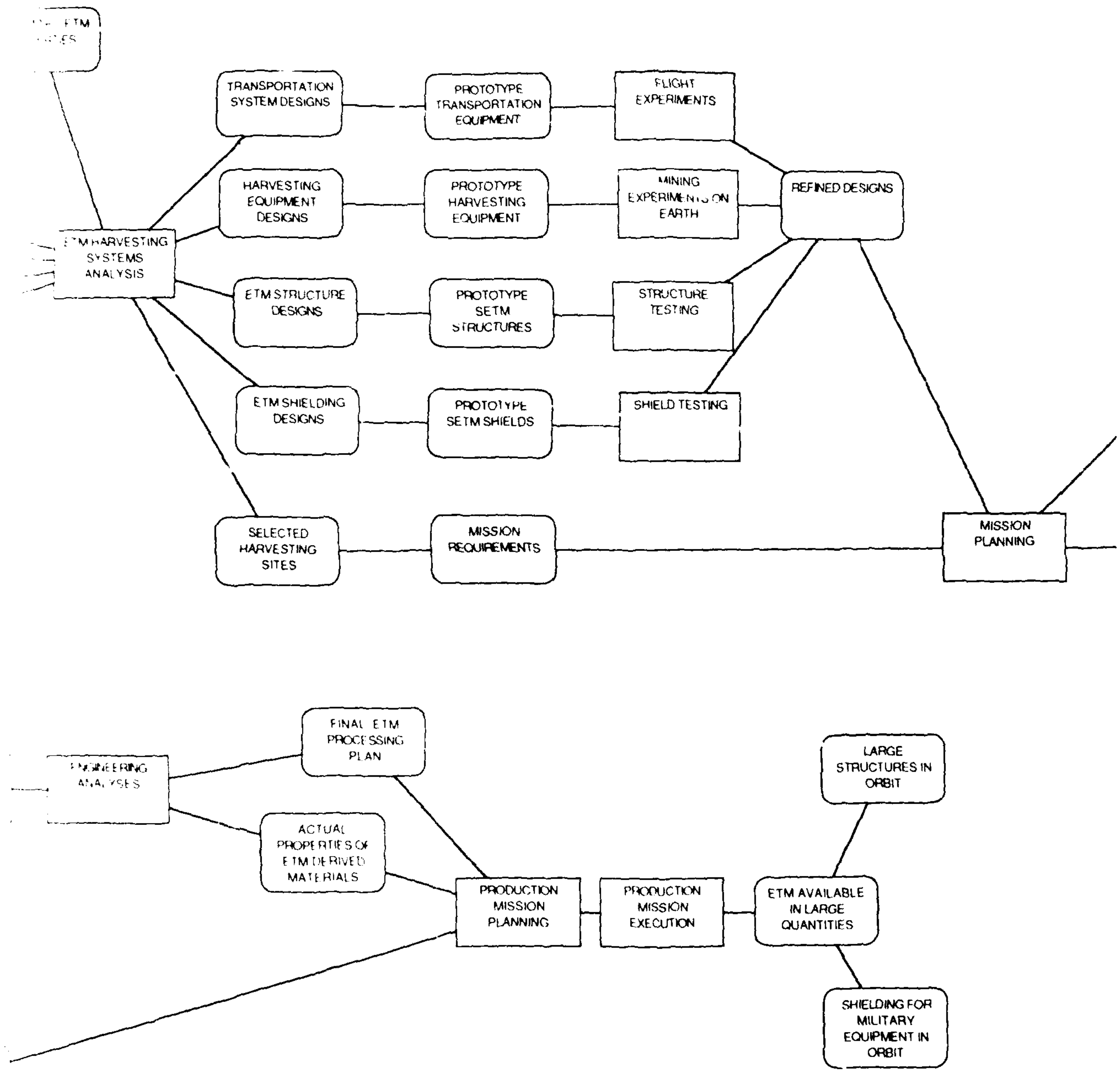


Figure 19 Extraterrestrial Material Harvesting Plan

3.4 R&D Program in Robotics

Although the actual progression of events may not turn out to be exactly as proposed here, the decisions about where to invest research and development must be made in the near term. If the goals described here, or similar goals for military robotics in space are to be realized, then research and development in certain areas are necessary now.

3.4.1 Important Guidelines

The important guidelines that should influence what R&D should be undertaken are

- Pursue R&D in parallel on all components of the technology.

- Use the advances being made in industrial robotics and build on them.

- Capture as much design data as possible in machine-readable form to provide a knowledge base for future AI software.

- Design all equipment with regard for the future, with attention to flexibility (multiple functions), extensibility (new functions), and growth (additional capacity).

3.4.2 Robotics Research Areas

Robotics research areas are noted in Figure 20. This is a schematic representation of any autonomous robot, emphasizing the software in its relation to the robot sensors and effectors. All of the parts, indicated by rectangles and circles, need R&D for military robots in space. The need for R&D of the technology for sensors and effectors has already been mentioned, primarily in connection with dexterity—a functionality that clearly requires improvement before autonomous robots can perform tasks that will be required in space. More sensitive, broader bandwidth, sensors will be required. Intensive R&D of sophisticated, very dextrous hands, more accurate and suitable for use in space, should be pursued. The parts labeled interpretation, control, and generation—software parts—also require improvement to achieve the dexterity and mobility that will be needed for space robots. Techniques will be needed for the fusion of multisensory information and the use of stored data about objects. New or improved algorithms will be needed to accomodate improved sensors and control improved effectors. The parts labeled AI (artificial intelligence) and KB/CDB (knowledge base/CAD data base), are essential for autonomous operation.

AI research areas are indicated in Figure 21. Artificial intelligence is a critical part of the technology that is required for autonomous robots. It will enable robots to act without explicit instructions from humans. AI software will need general-purpose and task-related information, in the form of a knowledge base, to decide what to do in response to high-level commands from humans, messages from other robots, and unexpected events. Geometric information, possibly in the form of a CAD data base, about the shape of each object

with which the robot must work, navigation information, communication, and the locations and actions of other robots. Artificial intelligence also will coordinate perception and action according to plans produced by the AI software. It will coordinate information exchange with humans, automated equipment, and other robots. It will also combine information from sensors and extract meanings relevant to the current task. It will coordinate real-time motion of hands, arms, and propulsion systems. It will handle information from transducers about internal and external events and conditions, as well as output transducers that produce motion or energy emissions and that control internal processes in the robot.

The objects with which an autonomous robot in space must deal will not be static but will change in time as a result of the actions of the robot and other forces, including other robots. The creation of AI software that can reason about such an environment will require extraordinary progress. The ability to plan a sequence of actions to carry out a task in such a dynamic environment is crucial, and the research that has been done in this area has not been extensive. In fact, little progress has been made during the past two decades.

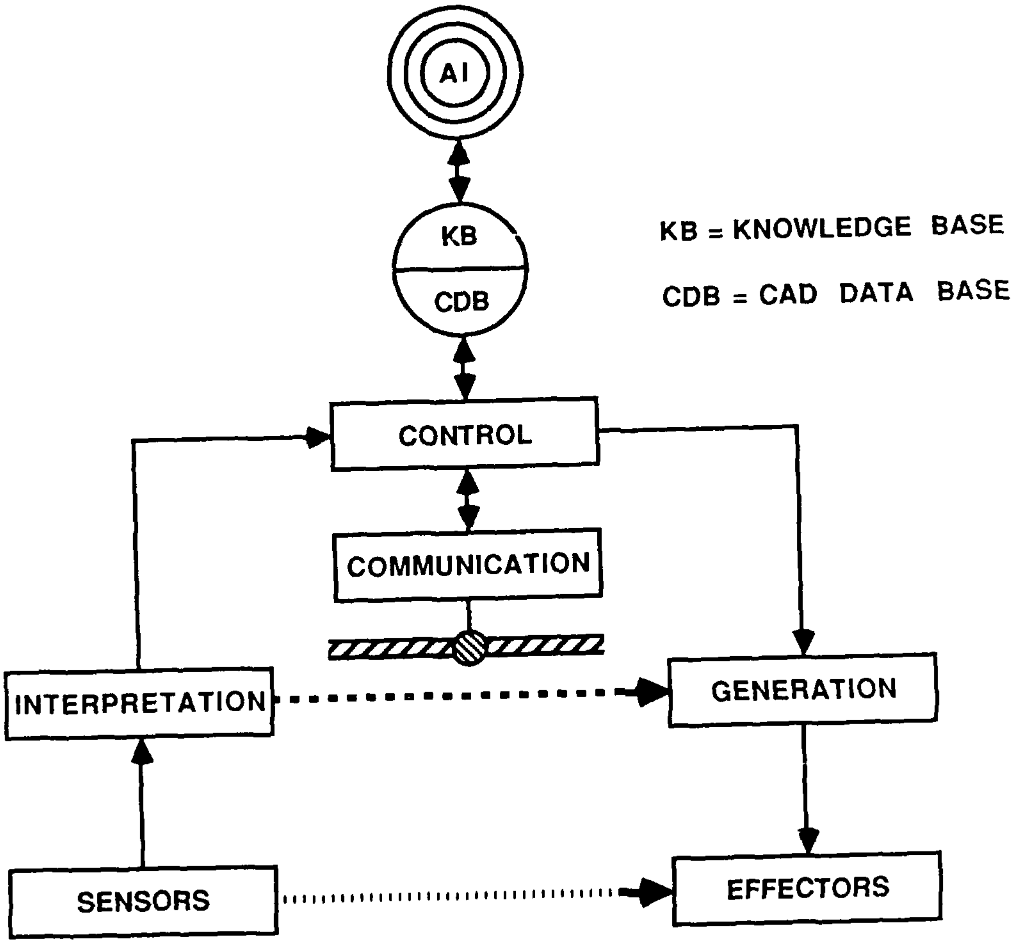


Figure 20 Robotics Research Areas

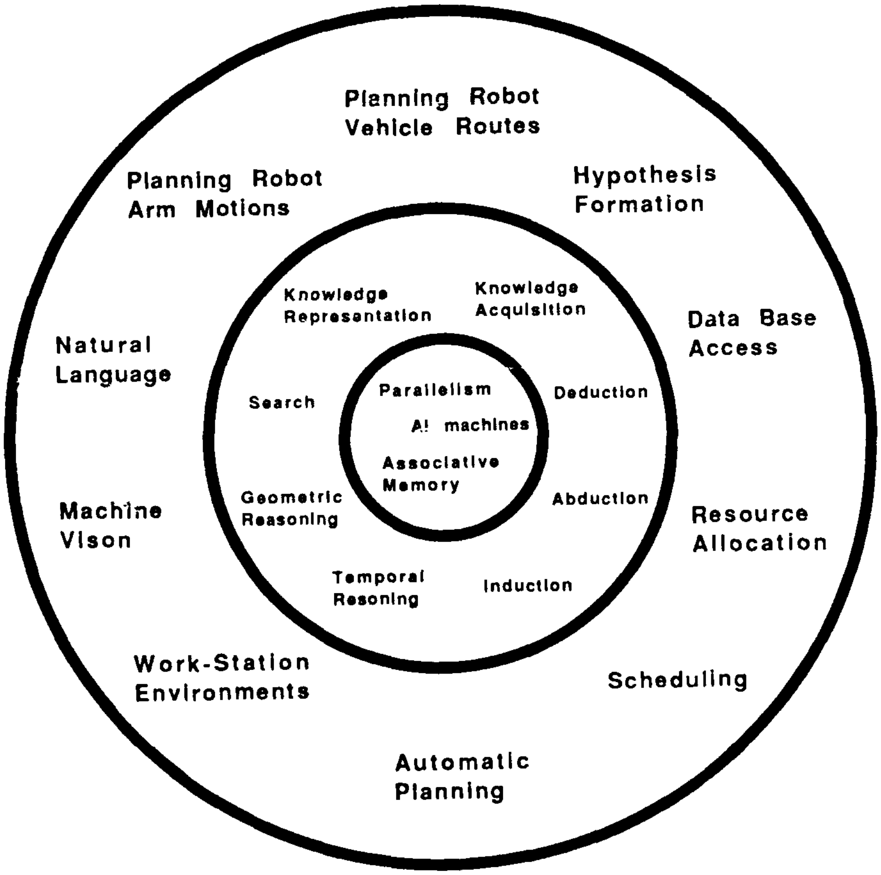


Figure 21 AI Research Areas

4 COMMENTS AND COUNTERPROPOSALS

The attendees at the workshop on 28 July 1986, divided into five groups to discuss the major topics covered by the strawman plan presented by SRI:

- Inspection, servicing, maintenance, and repair, chaired by Dr. James S. Albus.

- Construction in space, chaired by Dr. Kelli Willshire.

- Manufacturing, chaired by Mr. James E. Hollopeter

- Extraterrestrial harvesting, chaired by Prof. Theodore J. Williams

- Research and development, chaired by Prof. Robert Cannon.

The findings of the working groups, developed during parallel, working sessions, were presented and discussed with the reassembled participants. In general, the findings supported the concepts that had been presented in the strawman plan.

4.1 Inspection, Servicing, Maintenance, and Repair

The group that reviewed the inspection, servicing, maintenance, and repair aspects of SRI's strawman plan had a number of comments. It noted that SRI's plan needs a better statement of operational needs. Any plan for servicing must start with an understanding of the requirements. Also, a plan for military space robotics should make full use of related NASA developments, e.g., Goddard's flight telerobot servicer.

The group supported the need for designing satellites to be servicable, and suggested the establishment of "recommended practices." It proposed recognition of an interface between the servicing robot and end-effector tool. In the future, the satellite designer should be responsible for the design of end-effector tooling as well as the satellite

This group also stated that the key problem is knowledge representation in the data base that is used for inspection, servicing, maintenance, and repair. This problem requires long-term research, but also needs short-term solutions, because hardware is being designed in the short term for which the data need to be captured for future servicing.

DARPA's role was also questioned. The group thought that DARPA should be involved in areas where it has the greatest strengths: computing systems, intelligence (planning), architectures, and advanced systems. Specifically, DARPA's research in the following areas is important for inspection, servicing, maintenance, and repair:

- Intelligence
- Real-time planning
- Geometric reasoning
- Advanced manipulators: hands and actuators
- Knowledge representation
- Advanced simulation tools.

The group requested a diagram that shows how DARPA's research and development in these areas relates to users, NASA, SDI, Air Force, and the aerospace industry.

Lt. Jane Daugherty, from the Air Force Space Division, described the SAMS (Space Assembly, Maintenance, and Servicing) study being conducted by the Air Force and several contractors (TRW and Lockheed Missiles and Space Company). The SAMS approach will integrate DoD and NASA developments, and encompass operations on the ground, space transport, and activities in space. It expects to provide an initial support capability by 1995, with a transition to full support by 2010. The current SAMS study will be completed by 1 June 1987. The group recommended that the design reference missions created for the SAMS study be considered in connection with any plan for military space robotics.

The report by the group on inspection, servicing, maintenance, and repair concluded by noting some of the features that it found missing from the strawman plan, viz., an overall system architecture that integrates planning, control, knowledge, sensor fusion, communication, teleoperation, and supervisory control. The plan also lacked consideration of modularity, extensibility, and upgradability, according to the group.

4.2 Construction in Space

The group that reviewed aspects of the plan that dealt with construction in space had several comments on the critical issues that were presented in the plan, and added some of its own. It noted that the type of structure and its use will dictate the needed capability of a robot or teleoperator, and that the required reach of a robot, for example, will be directly influenced by tasks that it has to perform. The group stressed the need for attention to the mechanics of structures in space, since our knowledge about this subject, especially dynamics, is incomplete. The mechanics of structures in space need to be understood before sastisfactory designs for construction robots can be undertaken. The problems associated with reaction mass are always present.

Other issues noted by the group included the added difficulty of structural design when the design must be for construction by robots. The design of structures should not be isolated from the design of the payload or equipment to be carried by the structure. Contamination in construction is a problem and may require some form of "garbage" collection. Also, the group noted that autonomy of construction robots will be achieved slowly, by degrees, over a long period. The strawman plan did not include specific time lines, nor did it address logistic issues.

With regard to the demonstrations of construction by robots, the group noted that the shapes of construction materials can be designed to simplify handling by robots. The demonstrations should include more cooperative tasks by multiple robots. The only cooperative task that was illustrated showed two robots holding the same strut. The location of the control center was not shown, whether on the ground, on the orbiter, or at the station.

Economic issues were not addressed in the strawman plan, for example, a comparison of the time and cost of EVA operations with the time and cost of robots. Other important alternatives require cost analyses to decide. Deployable structures are alternatives to structures constructed in space and special-purpose, ad hoc, construction automation is an alternative to general-purpose construction robots.

4.3 Manufacturing

The group that reviewed manufacturing revised the strawman manufacturing R&D plan, aiming for an optimum mix of automation and manual manufacturing processes rather than the completely automatic process that is the goal of the strawman plan. This adds the activity of determining the optimum mix of automation and manual methods to the plan. The group also added a data-management system to the manufacturing R&D plan. It stressed the importance of capturing data about objects while they are being manufactured. It recommended also that designs for manufacturing processes should be verified first by simulation and second by prototype testing before being released for production. Multiple feedback paths can help in the evolutionary improvement of the process. The plan recommended by the group eliminated the boxes in the strawman plan labeled *Fully Automated Manufacturing Processes* and *Automatic Launching* but placed added emphasis on the boxes labeled *Design Principles for Automated Servicing*, *Automatic Manufacture of Vehicle Sections*, and *Automatic Mating of Vehicle Sections at Pad.*

4.4 Extraterrestrial Material Harvesting

The group that reviewed the ETM harvesting part of the strawman plan reported that the strawman plan is mainly a harvesting (mining) research program and that another plan is needed for manufacturing useful products with the harvested material. Also, a plan is needed for transportation of products from the harvesting site to earth orbit. The strawman plan is restricted to large structures and shielding materials. It does not address metallic materials and products made from such materials. Also, the strawman plan does not consider other uses for the harvesting site such as earth surveil-

lance or command, control, and communications. The group recommended an early analysis of the moon versus asteroids as a harvesting site: metallic versus volcanic moon sands. It noted that mining methods on asteroids will be much different because of gravitational effects.

Robotics research is needed for extraterrestrial harvesting in the areas of

- New representations for shapeless geometries, i.e., the material being mined.

- Handling machine-machine interactions of machines that perform different functions such as dig, load, or haul.

- Force cognition and force intrinsic manipulation: the "breakout problem."

The group pointed out that commercial mines do not have sufficient incentive to develop the automation that will be required. A fully automated process is too optimistic. Some human participation, with automation and robotics, will be optimum. Extraterrestrial harvesting is a 15-to-20 year program. The robotics technology is achieveable, but the requirement for ETM is questionable.

4.5 Research and Development

The group that reviewed the strawman plan from the point of view of research and development was critical. It stressed the need for a more carefully thought out approach to military space robotics, with more use of simulation and laboratory testing on the ground before demonstrations in space. Also, it urged that the unique aspects of military space robotics be stressed, without attempting to move the whole spectrum of industrial robotics. It did not believe that research and development of robotics for ground manufacturing would be appropriate.

The group found that the strawman plan was mostly a hardware plan, and recommended that companion software be development. A sequence of military space tasks that will tax software should be defined. Then both mechanical and software (artificial intelligence) technology development can be focused to accomplich the defined tasks. Simulation and testing on the ground should be thorough before undertaking more expensive demonstrations in space.

The R&D of robotics for military space applications should stress the unique requirements of space such as zero gravity, vacuum, radiation, and thermal conditions. Manipulators, for example, will be different from those on the ground and, therefore, will need special attention.

The missing parts of the strawman plan, as reported by this group, were software, modeling of processes, descriptions of end effectors, and determinations of the appropriate sizes of robots. The group urged an R&D plan based on a careful selection of requirements for space and adequate testing in the laboratory before demonstrations in space. It stated that the first five demonstra-

tions proposed in the strawman servicing R&D plan, in which industrial robots, such as Pumas, would be flown or launched into space, could better be done on the ground.

5 CONCLUSIONS AND RECOMMENDATIONS

In brief remarks, Dr. Saul Amarel, Director of DARPA ISTO, indicated that DARPA recognizes the importance of military space robotics and will direct more effort in that direction. DARPA is already supporting much of the key technology and will manage its programs to ensure that the technology needed for future military space programs such as SDI will be available.

Col. James L. Graham, Jr., SDIO, concluded the workshop by stating that the day had been well spent and that, in general, the strawman plan, with some of the revisions recommended by the workshop groups, was going in the right direction. The architectrure needs to be laid out in more detail and priorities for R&D set in the context of a total architecture. The technology should draw on past and current work wherever it is applicable, for example, in undersea robotics or in mining. The plan should be coordinated with the SAMS study. Cost estimates and studies of design trade-offs that consider costs and benefits are most important. The planning effort should continue towards a total, integrated plan.

The ommissions and questionable parts of the strawman plan presented by SRI were identified by the workshop participants. The strawman plan, with the comments of the working groups, constitutes a valuable foundation for a broad plan of action. More work is needed to define requirements, examine costs, and add missing pieces of the plan, but it represents a comprehensive approach to development of military space robotics. It can help to establish priorities for research and development and lead to an earlier realization of important national-security objectives. The workshop did increase the awareness of the military space community of the potential of robotics technology, some of it already available. It also emphasized the importance of a broad, comprehensive, and far-reaching plan, encompassing design, manufacture, launch, and maintenance. The beginnings of the needed plan, established here, should be used as the foundation for a continuous planning effort that includes all of the interdependent elements of military space robotics.

LIST OF ACRONYMS

AI	Artificial intelligence
ALV	Autonomous land vehicle
A&R	Automation and robotics
ASV	Adaptive suspension vehicle
CAD	Computer-aided design
CDB	Computer-aided-design data base
DARPA	Defense Advanced Research Projects Agency
EML	Electromagnetic launcher
ETM	Extraterrestrial materials
EVA	Extravehicular activity
FY	Fiscal year
ISTO	Information Science and Technology Office
JPL	Jet Propulsion Laboratory
KB	Knowledge base
MIT	Massachusetts Institute of Technology
MRMS	Mobile remote manipulator system
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
OMV	Orbital maneuvering vehicle
OTV	Orbital transfer vehicle
R&D	Research and development
RMS	Remote manipulator system
SAMS	Space assembly, maintenance, and servicing
SDI	Strategic Defense Initiative
SDIO	Strategic Defense Initiative Organization
SETM	Simulated extraterrestrial materials

Appendix

ATTENDEES AT DARPA WORKSHOP

Attendees at DARPA Workshop

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